Georg Eisner

EYE SURGERY

An Introduction to Operative Technique

Second, Fully Revised, and Expanded Edition
Translated by Terry C. Telger

With 546 Figures, Mostly in Color
Drawings by Peter Schneider

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HANS GOLDMANN:

*"... I am not manually skilled by nature,
so when it came to surgery I had to carefully ponder,
and try to understand rationally,
each step of the procedure..."*

(From a casual conversation)

PETER NIESEL:

*Purely intuitive skills are difficult to analyze.
The underlying causes of success or failure remain obscure.
This may be why the operative methods
described by one author are often less successful in other hands:
While the method has been learned, the craftmanship has not.
Experience, dexterity and intuition are not conscious processes
and are thus difficult to transfer to others.
The present book is concerned with finding a rational basis
for specific surgical manipulations.*

(From the introduction to the first edition of Eye Surgery 1978)

Preface

The second English-language edition of my book *Eye Surgery* is almost a new book. This reflects the developments during the ten years since the first manuscript was completed. Indeed, the changes have been so far-reaching that a fundamental different ophthalmic surgery has evolved. In the process, a new "way of surgical thinking" has emerged, calling for extensive revisions even in a book that is concerned with the elucidation of basic principles rather than with individual methods.

In keeping with modern developments, it has been necessary to add new chapters to this book and revise the old ones. The revisions took the author, working in his spare time, several years to complete.

While a book by one author has the advantage of being uniform in its style and presentation, it also has shortcomings due to the limitations inherent in a single-author work. It is my hope that, on the whole, the advantages will outweigh the shortcomings.

Though singly authored, the book would not have been possible without the help of others. It has thrived on the friendly exchange of ideas at our University Eye Hospital in Bern – an interchange that was already lively when the first edition was created, while Prof. Hans Goldmann was still clinical director, and which has been carried on by his successors. I am indebted to Prof. Peter Niesel, who based on his tireless research into causes and approaches offered important suggestions for the first edition and continued to offer helpful comments during the development of this second edition. Besides his daily support, he critically reviewed the first chapter on spatial tactics and helped to present the material with greater clarity and precision. I am grateful to Prof. Franz Fankhauser for reviewing the chapter on laser surgery. I also express thanks to the staff physicians and residents at our clinic, who by their useful questions and comments contributed many good ideas.

The number of illustrations has been expanded to 546. I was pleased to rely once more on the help of our university illustrator, Mr. Peter Schneider, who, in addition to his technical competence as an artist, displayed an insight and critical ability which clarified and enhanced my ideas. Although the new illustrations took a great amount of time and effort to complete, Mr. Schneider accomplished the job with patience and uncompromising accuracy. The reader will readily appreciate the quality of his work, a quality attested to by the fact that many of his drawings have since been reproduced in other books. I am very grateful to him.

I also wish to thank the translator of the German text, Mr. T.C. Telger. After his outstanding work on the first edition, I was greatly relieved to learn that he could undertake the job – a job made more difficult by the fact that the novel approach and new terminology in this book made it necessary to incorporate terms from other technical fields. Anyone familiar with the difficulty of reformulating complicated German syntax into readable English will appreciate his achievement.

My thanks go to Mrs. F. Meier-Gibbons MD and to Dr. Walter Lotmar for the careful proof-reading.

I express special thanks to my secretary, Ms. Christine Lehmann, for her tireless work in typing and retyping the text and its revisions. Her diligence and reliability were an important asset.

I also wish to thank Hans Grieshaber (Ophthalmic instruments Schaffhausen, Switzerland), Alcon Ltd. (USA), and Pharmacia AG (Uppsala, Sweden) for their financial support in the production of this book. Otherwise the many illustrations would have made the cost of the book prohibitive. With their assistance, it was possible to keep the didactic concept of the book intact.

I am again grateful to the staff at Springer Verlag for all their care and effort in the production of the book. They deserve recognition for the fact that the first German-language edition of *Eye Surgery* was listed among the 50 most beautiful German books by the Book Art Foundation of the Association of the German Book Trade.

Finally, I thank my wife Susanne and my children Daniel, Miriam, and Simone for their patience and understanding in accepting all the impositions upon family life that were inevitable during the creation of this book.

Bern G. EISNER

Contents

Introduction

Eye Surgery is intended as a "grammar" of intraocular surgery. However, is such a grammar really necessary? Is it not better to learn by practice than by theory?

What is the role of grammar in learning a language? Indeed, there are people who learn by practice alone. However, while practice may be a fine way to acquire language skills rapidly for everyday use, it is a laborious way to acquire more sophisticated language skills. It is difficult to recognize and correct errors without a knowledge of the basic structure of the language. Furthermore, grammar makes it easier to acquire new knowledge because it facilitates the integration of newly learned material into a whole. Actually, grammar shortens the path to perfection.

In the same way, it is possible to learn surgery by practice alone. But the road to experience is long, and if this is true of routine procedures, it is even more true when it comes to dealing with complications, i.e., finding optimum solutions in unexpected situations. I do not believe that the trial-and-error quest for experience is compatible with the interests of the patient. A knowledge of surgical "grammar" shortens the learning process. Furthermore, it helps in comparing different methods and weighing their advantages and disadvantages. Finally, a mastery of grammar makes it easier to develop new methods, because the basic principles, once learned, can be applied to novel situations in which experience is necessarily lacking.

The present book is tailored to this "grammatical" way of thinking. It describes basic principles of operating technique rather than specific methods. Like a language grammar that is concerned less with what is said in the language than with how well it is expressed, *Eye Surgery* focuses not on *what* is done but on *how* something is done.

And just as the length of the paragraphs in a grammar book does not necessarily reflect the frequency of the problems ("the rules are usually shorter than the exceptions"), the lengths of the sections in this book do not correlate with the practical frequency of surgical situations. If selected problems are presented, they are merely examples intended for training the reader in a surgical way of thinking that will prove valuable in entirely different and perhaps unexpected situations.

Our grammatical approach is appropriate for the standard procedures in the anterior segment of the eye, which usually are performed on normal tissue in a normal anatomic position. For such tissues whose properties are reasonably predictable, the surgeon can rely on geometrical and physical principles. This applies much less in surgery of the posterior segment, however, where we are dealing with pathologically altered tissue that has been displaced from its original position. The primary concerns of the surgeon are the careful clinical evaluation of the pathology and the development of a strategy appropriate for that pathology. The "grammatical" aspects in this type of surgery play a minor role. Therefore, posterior segment surgery is not specifically treated in this book. However, a structured approach can be derived by analogy with the rules for surgery of the anterior segment, i.e., space-tactical requirements, instrumentation, the treatment of lamellar and elastic tissues, etc. When faced with pathology, it is the surgeon's task to recognize which of the respective rules are applicable and to find the best solution.

One point must be emphasized: Just as a grammar cannot replace a language textbook, this book is not meant to replace textbooks on ocular surgery. Here we tend to assume that the reader is already familiar with standard operative goals and methods; and when we do detail the steps in a specific procedure, it is only for the purpose of illustrating essential technical principles. A clinical evaluation of specific operations is outside our present scope.

Every learning process poses a dilemma: The whole cannot be known without understanding its parts, and the parts cannot be grasped without understanding the whole. A "grammar book" can be a helpful roadmap on this complicated path.

The Paradox of High Success

kleine verbeteringen richting 100%
moeilijker aan te tonen, maar:
relatief belangrijker bij grote groepen.

50% -> 55% blijft 1:2
90% -> 95% 1:10 -> 1:20

Our goal in studying principles of surgical technique is to achieve the highest possible rate of success. Yet the closer we come to this goal, the more difficult it becomes to perceive the result of our efforts. The reason for this is what I call the "paradox of high success" – the curious fact that, as success rates improve, it becomes increasingly difficult to substantiate further improvements, because they become

- increasingly less apparent
- and increasingly difficult to prove.

The reason for the poor *perceptibility* of increments at high success levels stems from the practice of expressing success rates as percentages. However, the significance of a percentage change depends on whether it occurs at the middle or extreme end of the percentage scale. For example, a 10% improvement from 45% to 55% means very little, because both rates imply that there is roughly one success for every failure. Thus, the success rate (about 1:2) remains essentially unchanged despite the percentage improvement. In contrast, an improvement from 80% to 90% means that, where formerly we could expect about 5 successes for every failure, we can now expect about 10. In this case, then, the 10% improvement has led to a doubling of the success rate. Following this trend toward the extreme end of the scale, we will find that percentage improvements that appear negligibly small have a profound effect on the success rate. Thus, a rise of only 1% from 98% to 99% means that, where formerly we could expect 50 successes per failure, we can now expect about 100. A further improvement of only 0.5% beyond this point, from 99% to 99.5%, would be a tremendous advance, implying that only 1 in 200 patients would be at risk for failure.[1]

As the percentages rise, of course, there is a corresponding increase in the intellectual and material investment necessary to effect the improvement. Whereas little effort is needed to boost the rate from 45% to 55%, an increase from 80% to 90% calls for considerably greater know-how and technical expertise, while an increase from 99% to 99.5% demands a tremendous investment indeed. The basic problem is that, as success rates climb, it becomes increasingly difficult to justify the expense necessary for further improvements, since the improvement may not be amenable to statistical proof.

This brings us to part two of the "paradox of high success": the *unprovability* of extremely high success rates. The case numbers necessary for statistical proof increase dramatically with the success rate. For example, proof ($p < 0.01$) that a success rate of 80% has been raised to 90% by a new technique would require a data base of 250 cases. Proof of improvement from 98% to 99% would require about 2900 cases, and proof of a 99% to 99.5% increase would require about 5800 cases. Clearly, the case numbers necessary for a valid statistical study (one involving comparable patient populations, the same operator using a constant, standardized technique over the course of the study, and standardized follow-up procedures) cannot be achieved in practice. This implies that extremely high success rates cannot be proved.

I address this problem at the start of the book in the hope that the reader who seeks to optimize his surgical technique through intensive study will not become discouraged. Even though the results of his efforts may not be obvious or provable, the certainty of having done his best for the individual patient – *always the primary concern* – will still bring him satisfaction and will motivate him toward further refinements of his technique.[2]

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[1] It follows that success rates are more easily appreciated when they are expressed as fractions.

[2] It is important for the surgeon to understand the paradox of high success not just for his own motivation, but also so that he can discuss the problem intelligently with political and administrative authorities who make funding decisions. Obviously it is difficult to justify the enormous costs of increasing a high success rate when the improvement is neither numerically impressive nor provable.

Tactics in Ophthalmic Surgery

Modern microsurgery has revolutionized the conduct of eye operations. Above all, it has changed the mode of *feedback* on which the surgeon relies to guide his manipulations. The classic concept of *tactile feedback*, in which the operator is guided by tissue resistance, has been largely superseded by a *visual feedback* that relies on the evaluation of spatial relationships. With tissue resistance no longer a critical factor in guiding the application of forces, it has been possible to develop finer instruments that are more in line with the demands of atraumatic technique.

But modern ophthalmologic microsurgery implies more than improved visualization and finer instrumentation. It embodies an entirely new approach to *surgical tactics* in general. The way of "classical" surgery is to accomplish a given task in a minimum number of steps, with each step achieving as many individual goals as possible. The success of this "synthetic" approach requires extremely high skill and dexterity on the part of the operator.[1]

This contrasts with the "analytical" approach of the microsurgical technique, which permits every surgical action to be broken down into its individual components. The advantage of this approach is that each step can be adapted to a specific situation, making it easier for the surgeon to deal with any complications that arise.[2]

Microsurgical technique, then, is characterized by an *increased number of individual manipulations*. While this has advantages, it also increases the potential for tissue lesions caused by inadvertent movements of instruments or tissues. Consequently, modern microsurgery is concerned not just with the intended effects of a surgical action (*offensive tactics*) but also with the avoidance of undesired side-effects on the surrounding tissues (*defensive tactics*).

Offensive tactics, also referred to as **tissue tactics**, include such actions as the grasping, division, removal, and uniting of tissues. The instruments used for these actions are forceps, knives, sutures, etc.

Defensive tactics may be subdivided into surface tactics and spatial tactics. **Surface tactics** are *passive* defensive measures in which protective materials such as plastic film or viscous substances are used to keep tissue surfaces from coming in contact with instruments, implants, or other tissues. **Spatial tactics** are *active* defensive measures in which surrounding tissues are protected by *maintaining or augmenting tissue spaces* to create sufficient room for the numerous micromanipulations. This can be accomplished by the use of hydrodynamic systems, viscoelastic materials, or "membranous implants" (Table 1).

Table 1. **Surgical tactics in ophthalmology**

	Tactical goals	Targets of surgical action	Instruments
Tissue tactics	Division Removal Uniting } of tissue	Cornea Iris Lens Vitreous Retina	– Knives – Forceps – Sutures
Surface tactics	Protection of surfaces	Endothelium Lens capsule Anterior hyaloid Inner limiting membrane	– Viscous materials – Plastic sheeting
Spatial tactics	– Maintenance or expansion of intraocular compartments – Blockade of connecting pathways	Intraocular chambers and subcompartments	– Hydrodynamic flow systems – Viscoelastic materials – Bubbles with surface "membranes" (gas, oil)

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[1] Examples of "synthetic" manipulations:

- The anterior chamber is opened in a single maneuver with a cataract knife or keratome. The incision requires simultaneous rotational movements about various points and thrusting movements of extreme precision (see Fig. 5.48). The slightest error will jeopardize the procedure by allowing premature collapse of the anterior chamber. The result is a unique type of incision profile; modifications and corrections are nearly impossible.
- Anterior capsulotomy with a forceps (see Fig. 8.44) excises and removes a piece of the anterior capsule whose size and shape are difficult to control. The slightest error may result in an inadequate capsulotomy, rupture of the posterior capsule, damage to the zonule, or unintended extraction of the whole lens.

[2] Examples of the "analytical" approach:

- By opening the anterior chamber with step incisions made on multiple planes, the surgeon can accurately control the shape and profile of the incisions (see Fig. 5.62) and modify them as needed. Each step requires special manipulations, but errors in previous steps can be corrected in subsequent steps, providing an increased margin of safety.
- Anterior capsulotomies can be performed in multiple "ministeps" (see Fig. 8.38) to create an opening of any desired shape and size. With each new step the surgeon is able to correct errors made in previous steps.

1 Spatial Tactics

Spatial tactics in ophthalmic surgery are concerned with the shape and volume of the globe and its interior compartments (Fig. 1.1). The objective is to alter these parameters or maintain them in a controlled way during the application of external forces. Spatial tactics provide the immediate context within which the cutting, removing, and uniting of tissues are performed.

The shape of an **intraocular chamber**, and thus its volume, is a function of its *wall tension*. This tension results from the physical properties of the wall tissue and/or from the pressure inside the chamber. For a given tissue, then, a change in the volume of the chamber is associated with a change in its internal pressure.

1.1 Pressure Systems for Regulating Chamber Volume

A *pressure system* is illustrated in Fig. 1.2. The pressure in a chamber P_{ch} is determined by the relation between the inflow volume (V_{in}) and the outflow volume (V_{out}). The pressure in the chamber will remain constant as long as the inflow and outflow volumes are equal (formula 4). However, the pressure cannot be set to a predetermined level just by stipulating the flow-through parameters because it is a ratio and, as such, P cannot be expressed in isolation from the other parameters in formula 5. A given pressure can be established and maintained only by a regulating system which measures the chamber pressure and uses the measured pressure as feedback to make appropriate adjustments.[1]

Of practical importance are the *extreme values* that can develop in a pressure system and the conditions under which they occur (formula 6): The highest pressure is the initial pressure (P_{start}), and the pressure inside the chamber approaches that value when the inflow resistance tends toward zero or the outflow resistance tends toward infinity.[2] The lowest pressure is the terminal pressure (P_{end}). It develops in the chamber when the inflow resistance tends toward infinity or the outflow resistance tends toward zero.[3]

When values are selected for the **initial pressure** and **terminal pressure**, it must be considered that these extreme values can indeed develop in the chamber under extreme conditions, so they should remain within limits that can be tolerated by the chamber.

In selecting the **inflow resistance**, very low values are advantageous because they permit the selection of a low initial pressure.[4] On the other hand, a high value is advantageous for the **outflow resistance**, as this makes it easier to stabilize the chamber volume. Free selection of the outflow resistance is limited by the fact that surgical goals prescribe minimal widths for openings. Thus, when planning the pressure system for a particular procedure, the surgeon should first define the outflow resistance and then adapt the other parameters to that value.

In surgical practice, then, the various types of **space-tactical system** that are utilized to control the shape and volume of intraocular spaces are classified according to their outflow resistance:

- systems in which the outflow resistance is so high that, under ordinary conditions, there is no drainage of the chamber contents, and no inflow is needed to maintain the chamber pressure (*no-outflow systems*, Fig. 1.3a);
- systems in which the outflow resistance is within limits that allow the pressure to be controlled by regulating the inflow and outflow (*controlled-outflow systems*, Fig. 1.3b);
- systems in which the outflow resistance is so low that a given inflow system is incapable of pressurizing the chamber (*uncontrolled-outflow systems*, Fig. 1.3c).

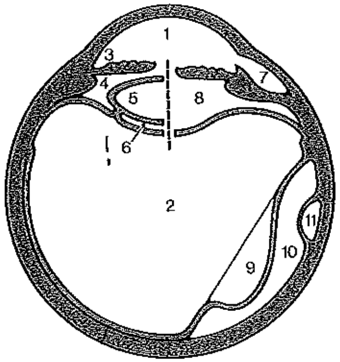

Fig. 1.1. The globe and its compartments
Left side: Normal anatomy
Right side: Pathologic spaces

Closed chamber systems:
1 Anterior chamber
2 Vitreous chamber

Open subcompartments:
3 Iridocorneal sinus
4 Iridocapsular interspace
5 Intercapsular sinus
6 Hyalocapsular interspace
7 Ciliosclerал interspace (after cyclodialysis)
8 Iridohyaloid interspace (after intracapsular cataract extraction)
9 Vitreoretinal interspace (after posterior vitreous detachment)
10 Chorioretinal interspace (after retinal detachment)
11 Sclerochoroidal interspace (after choroidal detachment)

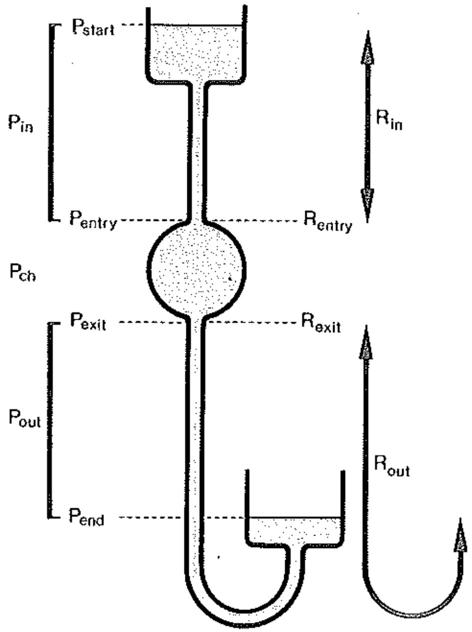

Fig. 1.2. Schematic diagram of a system for regulating pressure in a chamber. *Top*: inflow line. *Center*: chamber. *Bottom*: outflow line

[1] Inflow pressure $P_{in} = P_{start} - P_{entry}$
Outflow pressure $P_{out} = P_{exit} - P_{end}$

[2] Chamber pressure $P_{ch} = \frac{P_{entry} + P_{exit}}{2}$
for small differences between P_{entry} and P_{exit}: $P_{ch} = P_{entry} = P_{exit}$

[3] Volume of inflow $V_{in} = \frac{P_{in}}{R_{in}}$
Volume of outflow $V_{out} = \frac{P_{out}}{R_{out}}$

[4] $V_{in} = V_{out}$ when $\frac{P_{in}}{R_{in}} = \frac{P_{out}}{R_{out}}$
or $\frac{P_{in}}{P_{out}} = \frac{R_{in}}{R_{out}}$

[5] Inserting [1] and [2] into [4]:
$\frac{P_{start} - P_{ch}}{P_{ch} - P_{end}} = \frac{R_{in}}{R_{out}}$

[6] Therefore:
when $R_{in} \to 0$, then $P_{ch} \to P_{start}$
when $R_{in} \to \infty$, then $P_{ch} \to P_{end}$
when $R_{out} \to 0$, then $P_{ch} \to P_{end}$
when $R_{out} \to \infty$, then $P_{ch} \to P_{start}$

---

[1] In the absence of such a measuring system, one must rely on an "adequate" pressure as determined by visual observation of the chamber volume.

[2] As a practical example, the occlusion of a tightly inserted outflow cannula would produce an infinite outflow resistance.

[3] As practical examples, the inflow resistance approaches infinity when the inflow tubing is inadvertently bent; the outflow resistance tends toward zero when an outflow orifice is widely opened.

[4] As we will see later, however, low values are problematic when external forces act on the chamber. Limits are imposed as well by topographic factors (the size of the cannula).

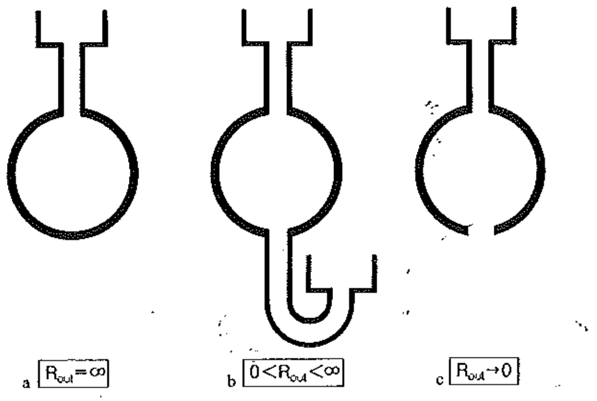

Fig. 1.3. Space-tactical systems

a No-outflow system: As outflow resistance tends toward infinity, no drainage occurs, so there is no need for inflow.

b Controlled-outflow system: The outflow resistance is finite and greater than zero. The available inflow capacity can compensate for the outflow.

c Uncontrolled-outflow system: As outflow resistance tends toward zero, the pressure in chambers open to the outside approaches atmospheric (=0)

1.1.1 No-Outflow Systems

No-outflow systems are technically straightforward. **Primary no-outflow systems** are those in which the contents of the chamber remain unchanged (Fig. 1.4.a, b). It is necessary only to introduce instruments into the chamber in such a way that the access opening remains *watertight*. Surgical options are limited, however, since no material may be removed from the eye, and such systems are suitable only for procedures involving the division of tissues.[5] Absolute no-outflow systems are procedures performed with lasers.

In **secondary no-outflow systems** the chamber is filled with a highly *viscous material* (Fig. 1.4c). Since the size of the outflow opening is not a critical concern in this system, bulky instruments and implants may be introduced into the chamber, and tissue fragments may be removed. Actually, uncontrolled-outflow systems can be converted to secondary no-outflow systems by filling the chamber with viscous material.

1.1.2 Controlled-Outflow Systems

The controlled-outflow system is a **regulating system** that uses a feedback mechanism to coordinate inflow and outflow. Theoretically it would be ideal to have an inflow capacity large enough to compensate for any outflow that might occur. In practice, however, there are constraints: Once the inflow limit is reached it becomes necessary to reverse the control mechanism and regulate the outflow so that it does not outstrip the available inflow capacity. With resistance-modulated outflow, the inflow capacity limits the permissible size of the outflow opening (Fig. 1.5a). With pressure-modulated outflow, this capacity limits the permissible level of the suction (Fig. 1.5b).

Controlled outflow systems imply that inflow ceases when outflow is obstructed. If continuous flow is required because the infusion must perform functions in addition to volume control (e.g., cooling an ultrasonic vibrator or a coagulator), it is essential to avoid total obstruction of outflow. This danger can be eliminated by providing a second, reserve outflow path in addition to the controlled-outflow path (Fig. 1.5c).[6]

1.1.3 Uncontrolled-Outflow Systems

If the inflow capacity is not adequate for a given outflow, the chamber volume can no longer be pressure-modulated. This is the case when there is a large chamber opening, whose lack of outflow resistance would require an inflow capacity of infinite size (Fig. 1.6a). In a chamber that has no inflow system, even the slightest leak will produce a state of uncontrolled outflow (Fig. 1.6b).

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[5] Such as capsulotomies, iridotomies, and synechiotomies.

[6] This is the case in phacoemulsification, where a deliberate "leak" is left in the corneoscleral opening next to the irrigating tube to ensure an uninterrupted flow of cooling liquid.

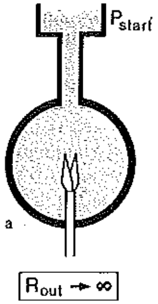

Fig. 1.4. No-outflow systems

a, b Primary no-outflow system: The high outflow resistance is based on the size of the outflow opening. A seal is obtained by adapting the opening to the instrument diameter.

a An inflow line may be connected to the chamber to alter its pressure (the initial pressure P_{start} becomes the chamber pressure).

b If just the existing chamber pressure is to be maintained, no inflow is required.

c Secondary no-outflow system: The high outflow resistance is based on the high flow resistance of the chamber contents, i.e., the chamber is filled with a material that cannot drain because of its high viscosity

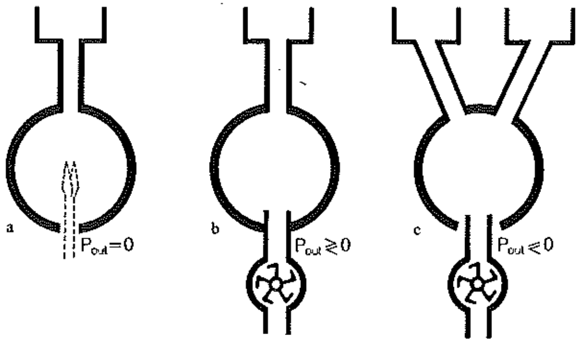

Fig. 1.5. Controlled-outflow systems

a Modulation of resistance: Outflow is controlled by modulating the resistance to drainage through a leaking outflow orifice. The necessary inflow capacity depends on the size of the leak at the outflow orifice, which should not be opened to a degree that would outstrip that capacity. The outflow pressure is constant (atmospheric pressure).

b Modulation of pressure: Outflow is controlled by a cannula whose junction with the chamber is watertight. The necessary inflow capacity depends on the negative pressure (suction), which should not be low enough to outstrip that capacity. The outflow resistance is constant (length and caliber of aspiration cannula).

c Combined modulation of pressure and resistance: The opening around the aspiration cannula is not watertight. Control is made more complex by parallel outflow paths, which are partly pressure-modulated and partly resistance-modulated. A correspondingly large inflow capacity is required, and a second inflow line may be advantageous

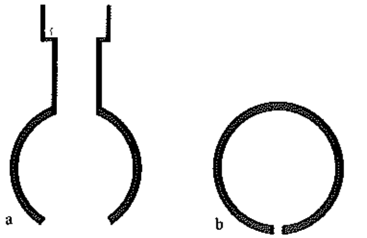

Fig. 1.6. Uncontrolled-outflow systems

a When the outflow resistance tends toward zero, infinite inflow would be needed to pressurize the chamber.

b If no inflow is supplied ($P_{in}/R_{in}=0$), even the slightest wound leak R_{out} will allow uncontrolled drainage

1.1.4 Effect of External Forces on Regulating Systems

The principle that a particular chamber volume correlates with a particular pressure and can be stabilized by maintaining that pressure is valid only as long as the pressure surrounding the chamber remains unchanged. If the ambient pressure rises, the pressure inside the chamber must also rise by a certain amount to maintain a constant volume.

It is not enough, then, to determine how effectively regulating systems can maintain a specified pressure. We must also determine how they behave in response to the application of external forces.

In chambers whose shape depends on pressure, the pressure inside the chamber will rise when its wall is deformed (Fig. 1.7).[7] If outflow from the chamber is possible (i.e., if the outflow resistance is finite), a portion of the chamber contents will gradually discharge. The pressure will fall until it again reaches the level imposed by the regulating system. This implies, however, that the chamber has lost some of its volume and has become deformed.

The rate at which this loss occurs is of practical importance. If the volume loss is abrupt, the surgeon has insufficient time to react. The safest systems, then, are those in which the pressure reacts very slowly in response to external forces.[8]

The critical factor in this regard is the *outflow resistance* from the chamber. The lower the resistance, the more rapid the volume loss. This loss is most rapid in an *uncontrolled outflow* system, where an applied force causes immediate deformation of the chamber. In a *no-outflow* system, on the other hand, the force causes only a rise in pressure. In a *controlled-outflow* system the rate of volume loss depends on the openings that are available for outflow. But in evaluating outflow, it should be realized that a primary inflow opening can become an outflow opening when the chamber pressure rises. This means that low inflow resistances are advantageous in a controlled-outflow system only when they serve to correct for pressure fluctuations. They are disadvantageous under the action of external forces because they make the system susceptible to volume loss.

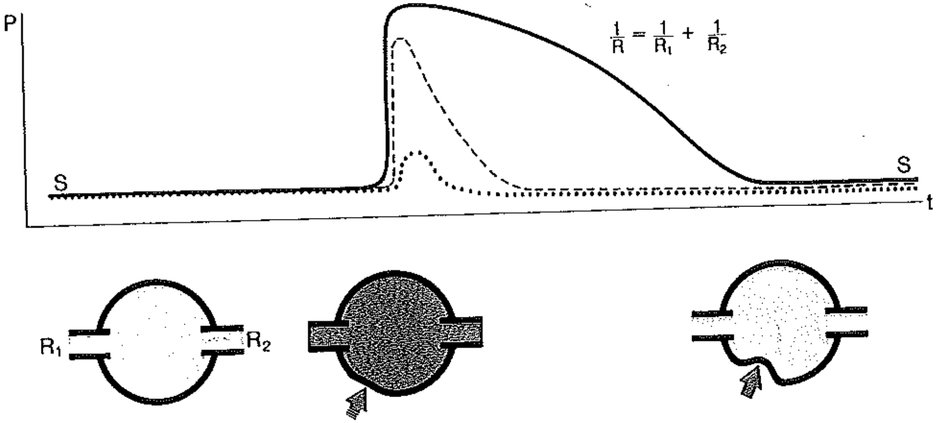

Fig. 1.7. Response of space-tactical systems to external forces. When the pressure in the chamber rises in response to external forces, outflow is increased until the pressure returns to the steady-state level imposed by the regulating system (*S*). Meanwhile the chamber is deformed, with maximum deformation occurring in the steady state. The outflow rate (for a given total elasticity) depends both on the level of the outflow resistance and on the inflow resistance

1.1.5 Basic Safety Strategy for Spatial Tactics

The *dilemma* in pressure-regulating systems is that the maintenance of a given pressure can ensure a constant chamber volume only as long as the environment is stable, but that maintenance of the given pressure means loss of volume from the chamber as soon as external forces are applied. Thus, if a system is chosen that is extremely fast in responding to pressure changes, it will also be very sensitive to external forces. This is taken into account in the **basic spatial safety strategy**: Optimum spatial stabilization is achieved by a control system that maintains a constant pressure by responding quickly to pressure fluctuations within the chamber (*intrinsic factors*). The problem of susceptibility to external forces (*extrinsic factors*) is solved by implementing measures to protect the chamber from the action of those external forces.

In the chapters that follow we shall describe first the space-tactical instruments that can be used to control intrinsic factors, and later we shall consider means for preventing the deformation of chambers by extrinsic factors.

1.2 Space-Tactical Instruments

Intraocular spaces can be maintained or expanded by the use of substances which, when introduced through a small access opening, can occupy a large volume inside the chamber, i.e., implants that can be injected through thin cannulas:

- *watery implants*, whose flow resistance depends chiefly on external friction, i.e., on the wall properties of the flow system;
- *viscous and viscoelastic implants*, which create resistance through high internal friction; and
- *"membranous" implants* (*bubbles*), whose efficacy is based on surface tension.

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[7] The extreme case being a spherical chamber, where any deformation causes a volume change and even the slightest deformation raises the pressure (see Fig. 1.41).

[8] Even when the globe is intact, external forces cause the intraocular volume to change. But aqueous drainage through the corneoscleral trabeculum occurs against such a high resistance that external deformation is effective only when sustained for a long period (e.g., scleral buckling in retinal detachment surgery).

1.2.1 Watery Fluids

Properties

Watery fluids have an extremely high molecular mobility and extremely low internal resistance. Even the slightest external force will cause displacement of the fluid.

The initial and terminal pressures of the fluid are determined by the **pressure sources**. In *gravity systems* they are determined by the height of the water column, which of course is limited by available space. *Pumps* can generate very high pressures, which require valves for their control (Fig. 1.8).

The initial and terminal pressures are extreme values. They cannot be used to calculate the pressure inside the chamber (see Fig. 1.2). If there is no precise regulating system, the surgeon's only option is to rely on "experience" for determining and maintaining the desired chamber pressure. But this experience is valid only for a particular system whose parameters are strictly maintained. One has to be aware of *disturbing factors* which alter pressures and resistances in unforeseen ways, causing the actual chamber pressure to deviate from empirical values. The *pressure*, for example, can be influenced by elastic phenomena associated with the presence of air bubbles or the use of soft elastic tubing. A change of pressure in the system can cause elastic energy to become stored and subsequently released, with corresponding effects on the shape and volume of the chamber (Fig. 1.9). **Flow resistances** in the system are subject to Poiseuille's law.[9] This law states that resistance to fluid flow through a tube is proportional to the length of the tube and inversely proportional to the fourth power of its radius. Thus, doubling the length of the tube increases the resistance two-fold, while halving its radius increases the resistance 16-fold. It follows, then, that even slight reductions in cross-section will greatly reduce the volume rate of flow (Fig. 1.10). Unnecessary constrictions should be avoided in a fluid transport system, and if such constrictions are necessary due to space limitations (e.g., cannulas inserted into the eye), they should be kept as short as possible (Fig. 1.11).[10]

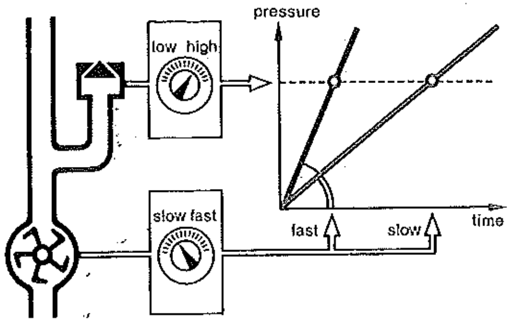

Fig. 1.8. **Control of pump-driven fluid transport systems.** The pressure level is limited by a valve and can be raised or lowered by adjusting the pressure dial. The speed at which this pressure level is attained depends on the delivery rate of the pump, which is controlled by the velocity dial

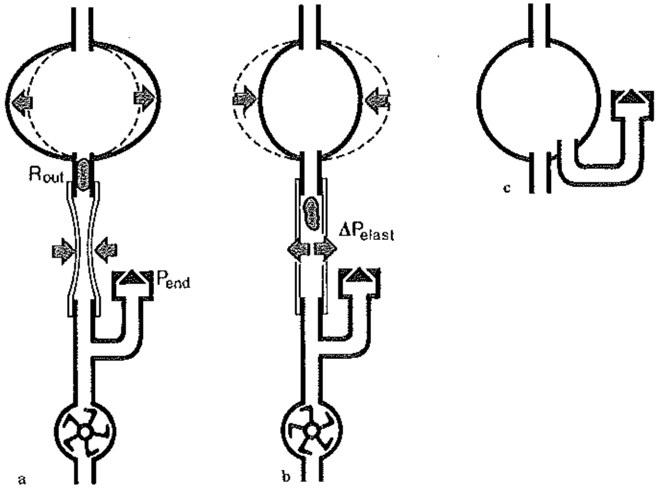

Fig. 1.9. Effect of soft elastic tubing on pressure control

a When a particle becomes lodged in the outflow cannula, the outflow resistance R_{end} rises precipitously. The pressure in the chamber approaches the initial pressure P_{start}, and the chamber wall expands. The pressure in the outflow tube falls, approaching P_{end}. But when this pressure, which is set by the valve, is reached the walls of the tubing have contracted (thereby storing elastic energy).

b When the obstruction is cleared, the pressures would return to the preset levels if the tubing were rigid. But with soft elastic tubing, the previously stored elastic energy is abruptly released and briefly augments the suction, causing a precipitous, unplanned pressure drop in the chamber.

c For reliable pressure stabilization, the valve should be connected directly to the chamber

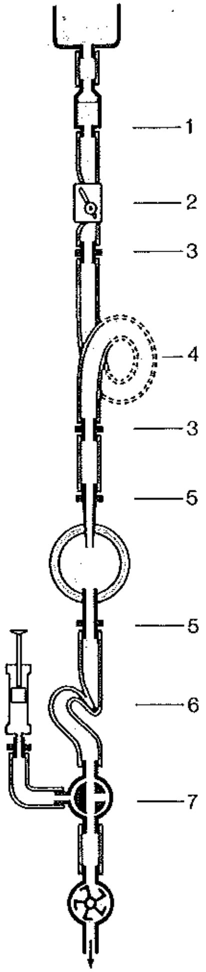

Fig. 1.10. Sources of increased resistance in the fluid transport path

1. Connector between tubing and drip chamber
2. Clamp-type flow regulator
3. Tubing connectors
4. Redundant extension tubing
5. Cannula
6. Kink in tubing
7. Connectors and lumina of three-way stopcock

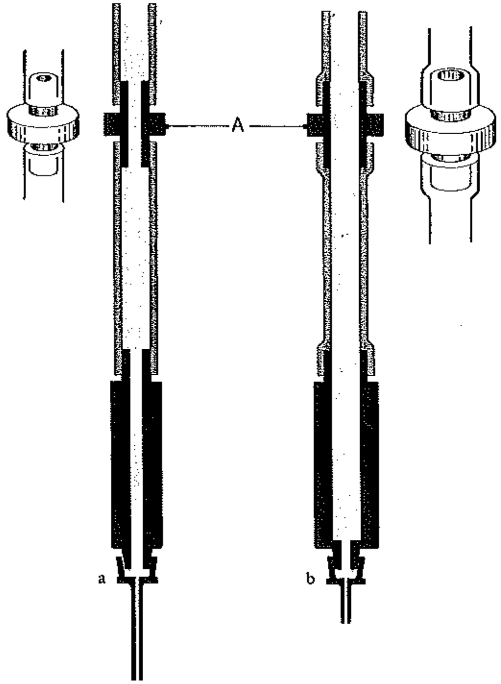

Fig. 1.11. High- and low-resistance transport systems

a *High-resistance system:* The tubing connector (*A*) and the handle of the cannula have a smaller inside diameter than the tubing itself. Therefore, in this arrangement the ends of the flexible tubes are not expanded at their connections with the rigid tubes.

b *Low-resistance system:* The lumen remains constant und unconstricted as far as the inlet of the cannula. Therefore, the ends of the flexible tubes must expand at the connections. The lumen of the handle should be wide, but this is not apparent from external inspection and must be checked before the equipment is procured. The cannula should be as short as possible to decrease resistance

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[9] Poiseuille's law: $R = c \cdot \frac{\eta \cdot L}{r^4}$
R = resistance
η = fluid viscosity
L = length of flow path
r = radius of lumen
The law applies to ideal fluids. For real fluids, the resistances increase by a significantly greater amount when the radius is decreased.

[10] Because computational means are not available for evaluating an optimally balanced fluid transport system, the system should be tested beforehand on a phantom chamber whose wall characteristics are like those of the chamber to be protected. In that way the response of the system to disturbances (e.g., obstruction of a tube and storage of elastic energy) can be tested and optimally adjusted.

Application of Watery Fluids

Watery fluids are distributed rapidly to all parts of the chamber, regardless of their site of introduction. Thus, cannulas do not have to be inserted deep into the chamber, and the conditions at the entry site are the only critical factor from the standpoint of spatial tactics.[11]

Resistance parameters relating to **instrument geometry** are not variable and depend on *cross-sectional dimensions:* lumen and external shape (Figs. 1.12 and 1.13). The **position of the cannula** at the entry site is variable, however. *Raising* or *lowering* the cannula reduces the outflow resistance, whereas *swiveling movements* of the cannula in a lateral direction increase it (Fig. 1.14). Thus, these movements are an important means by which the surgeon can regulate outflow resistance. On the other hand, movements of this kind can have significant adverse effects when performed inadvertently, especially when they are unnoticed by the operator. *Monitoring of the cannula position at the entry site*, then, is the most important safety measure for the application of watery fluids in spatial tactics.

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[11] The direction of fluid flow is immaterial from the standpoint of spatial tactics. However, if the fluid stream is used to achieve tissue-tactical goals (mobilization and transport of tissue particles), the position of the cannula tip is critical. This is discussed more fully in Figs. 2.18 and 2.23.

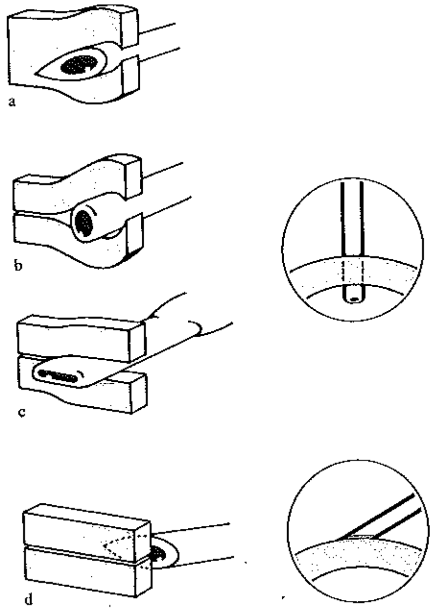

Fig. 1.12. **Methods of sealing the access opening with simple cannulas**

a When a cannula with a sharply beveled tip is thrust directly through the tissue it creates an opening that conforms exactly to the outside diameter of the cannula. Leakage does not occur.

b When a cylindrical cannula is inserted through a stab incision, the cross-sections of the cannula and incision are incongruent, and the opening around the cannula is not watertight.

c A flattened cannula conforms better to the incision and permits less leakage.

d When a cannula with a sharp bevel is applied to the incision such that its entire rim apposes snugly to the tissue, the injected fluid will itself open the incision, and the opening will conform exactly to the cross-section of the stream. It remains open only while the stream is maintained, and reflux cannot occur.

Note: Whereas the cannula is perpendicular to the tissue surface in **a**, **b** and **c** (*inset top*), the cannula in **d** is applied at an angle equal to the bevel angle of the tip (*inset bottom*)

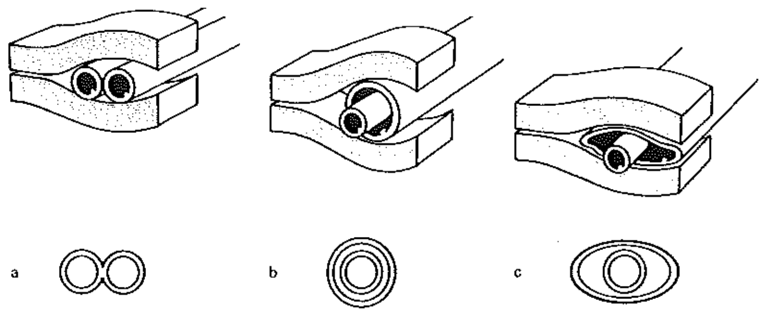

Fig. 1.13. **Double cannulas for infusion and aspiration.** Below the perspective drawings are cross-sectional diagrams in which the surfaces that critically affect flow resistance are shown in *red*. Inflow resistance depends chiefly on the lumen of the infusion cannula, while outflow resistance depends on both the lumen and external shape of the aspirating cannula.

a Parallel arrangement: Both cannulas are cylindrical with equal ratios of lumen to surface area. The total external cross-section of this arrangement is analogous to that in Fig. 1.12c.

b Coaxial arrangement: Fluid is infused through the outer tube and aspirated through the inner tube. The surface area bordering the stream in the outer tube is twice that in a circular lumen of equal diameter, creating a correspondingly high infusion resistance. Hence, the diameter of the outer tube must be relatively large to allow for an adequate infusion capacity, thus accentuating the problem of leakage around the tube (analogous to Fig. 1.12b).

c Coaxial arrangement with a soft outer sheath: Since the compliant outer tube conforms to the wound canal, the lumen can be enlarged without encountering the leakage problems in Fig. 1.12b[12]

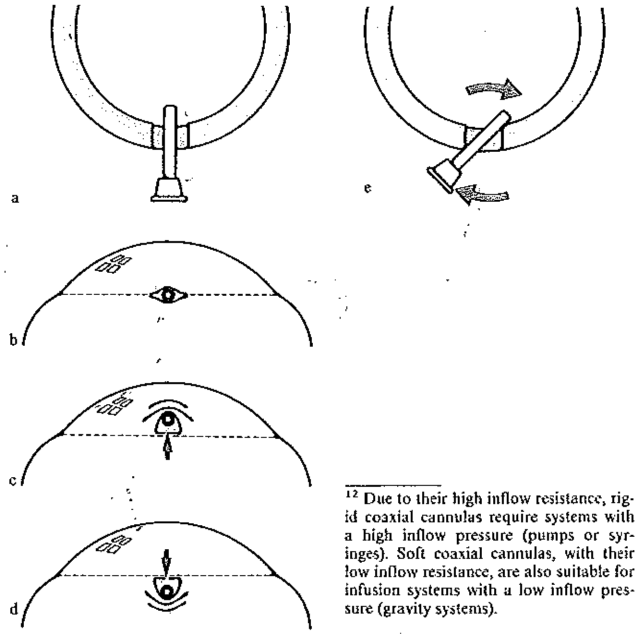

Fig. 1.14. **Effect of cannula placement on wound leak**
Left: Perpendicular movements of the cannula.

a Overhead view.

b Cross-section: When the cannula is precisely on the wound plane, the degree of leak depends only on its external shape (as in Fig. 1.12b, c).

c, d Vertical movements of the cannula increase the leak, and outflow resistance falls. Elevating the cannula (**c**) creates a fold in the chamber wall above the opening. The fold is visible when viewed from above. Lowering the cannula (**d**) makes a fold below the opening, and the surgeon is less likely to perceive the danger of increased leak adjacent to the cannula.

Right: Horizontal movements of the cannula.

e Slewing movements of the cannula may occlude the access opening and increase outflow resistance

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[12] Due to their high inflow resistance, rigid coaxial cannulas require systems with a high inflow pressure (pumps or syringes). Soft coaxial cannulas, with their low inflow resistance, are also suitable for infusion systems with a low inflow pressure (gravity systems).

1.2.2 Viscous and Viscoelastic Materials

Properties

Viscous and viscoelastic materials are characterized by their high internal friction. While flow resistance in watery fluids is determined chiefly by the wall characteristics of the perfused system (Fig. 1.15a), in viscous and viscoelastic materials it is determined largely by the specific rheologic properties of the material itself.

The basic difference between viscous and viscoelastic materials is that *viscous materials* behave like pure fluids and develop internal forces only when their volume is changed; shape changes have no such effect. *Viscoelastic materials*, on the other hand, develop internal forces when their shape and/or volume is changed, so they also have properties of solids.

In **purely viscous materials**[13] the resistance to flow is based on the relationship between the degree of viscosity and the lumen of the perfused channel (Fig. 1.15b). Flow properties are more complex in **viscoelastic materials**[14] in that the resistance to flow changes when the material is moved. As a model, we can think of the material as a tangled mass of elastically deformable molecular chains (Fig. 1.15c). The chains are deformed by the action of external forces, and once the forces are removed, the chains can return to their original shape. This process is time-dependent (Fig. 1.16). If the force is applied violently, the molecules pack tightly together and then rebound. If the force is applied more slowly, the molecules have time to rearrange. As a result, viscosity decreases as soon as flow commences, and the material flows more readily ("shear thinning") (Figs. 1.17 and 1.18).

During phases in which the material has *viscous* properties, the mechanical energy of friction is converted to heat. In phases where the material is in an *elastic* state, mechanical effects lead to the storage of elastic energy. It is characteristic of viscoelastic materials that their rheologic properties change continually during use, depending on the speed (change from viscous to elastic behavior) and duration of the impact (change from a high-viscosity to low-viscosity state).[15] The usefulness of a substance for specific surgical goals depends on the shear rate at which the material changes from one state to another.

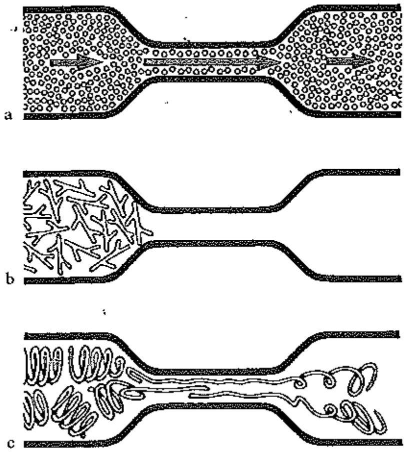

Fig. 1.15. **Behavior of flowing watery, viscous, and viscoelastic substances at constrictions**

a Watery fluids: As the channel narrows, the molecules speed up because equal volumes of fluid must traverse all portions of the channel per unit time.

b Viscous fluid: The relationship of the degree of viscosity to the lumen of the constriction determines whether or not the fluid can negotiate the constriction.

c Viscoelastic materials: The molecular chains deform when passing the constriction, and flow resistance decreases with increasing flow due to molecular rearrangement. Given enough space, the molecules will regain their original form

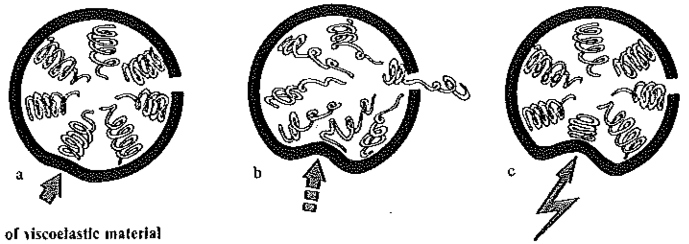

Fig. 1.16. **Behavior of viscoelastic material in a chamber deformed by an external force: significance of the time factor**

a When the force is applied gradually, the material displays viscous properties initially. The outflow resistance, defined by the viscosity and the size of the outlet, determines whether any of the material will be discharged.

b With continued application of the force, the material displays shear thinning as the molecules rearrange and conform to the outlet. This lowers their outflow resistance, and the material flows from the chamber at an increasing rate.

c When a shorter-acting, violent force is applied, the material behaves as an elastic body. The molecules deform without rearranging, and the force is stored locally as elastic energy. No material escapes from the chamber

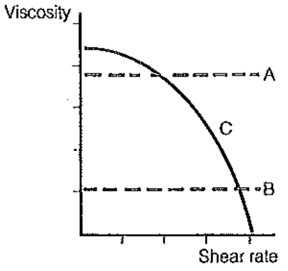

Fig. 1.17. **Viscosity and viscoelasticity.** Dependence of viscosity on shear rate (scale in log log units). Substance *A* has a high viscosity and substance *B* a low viscosity. Both are purely viscous, i.e., their viscosity remains constant with increasing shear rate. But in substance *C*, which is viscoelastic, the viscosity changes with the shear rate. The material is highly viscous at a low shear rate and becomes increasingly fluid as the shear rate increases. This property is called shear thinning ("pseudoplasticity")

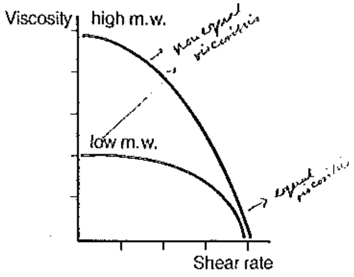

Fig. 1.18. **Dependence of shear thinning on molecular structure and concentration.** Viscosity depends on the volume occupied by the molecules in the flow channel (hydrodynamic volume). Maximum viscosity (i.e. at a low shear rate) is determined chiefly by the shape and length of the molecules (*molecular weight*), i.e., by the hydrodynamic volume of the undeformed molecular mass. Minimum viscosity depends on the *concentration* of the molecules in solution, i.e., on the number of optimally aligned molecules per cross-section in the flow.

The curves represent two substances of different molecular weights in the same concentration. At a low shear rate, the viscosity of the high-molecular-weight substance is higher; at a high shear rate, both substances display nearly equal viscosities

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[13] Viscosity = shear stress per shear rate.

[14] In a strict sense all fluids from water to gas are "viscoelastic," but the size and ratio of the viscous and elastic components vary greatly. In surgical use the term has come to denote viscous substances whose elastic component is so large that it can be used to achieve specific operative goals.

[15] Therefore viscosity data are of little value as a basis for comparing different viscoelastic products, since the data are valid only for a given testing method.

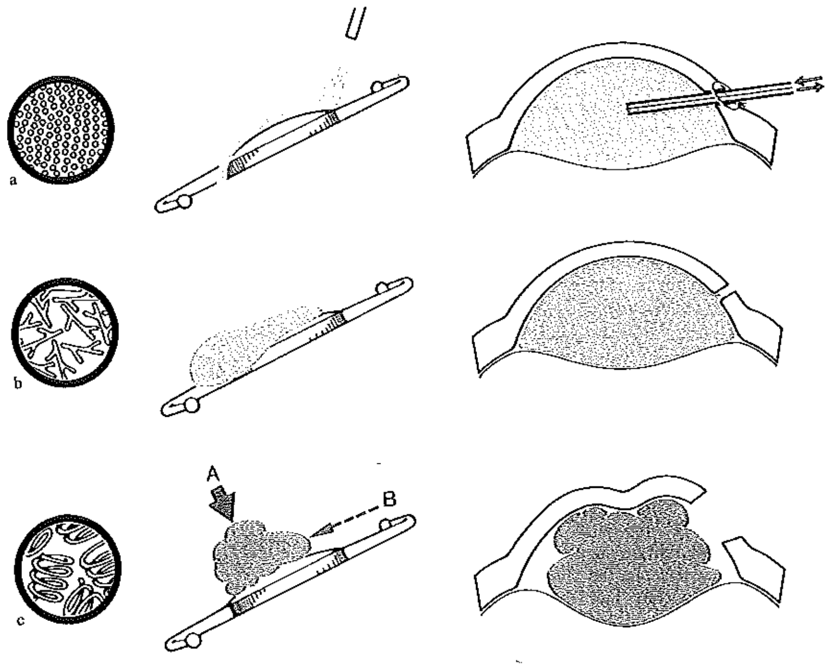

Fig. 1.19. Comparison of watery, viscous, and viscoelastic substances.
Left: Applications in surface tactics.
Right: Applications in spatial tactics.

a Watery fluids: Because of their very low viscosity, watery fluids are always applied in a continuous stream.

b Viscous substances flow evenly onto tissue and implant surfaces to form a stable, uniform protective coating. In spatial tactics, the efficacy of the substance (for a given viscosity) depends on the size of the drainage opening.

c Viscoelastic substances: A plug of viscoelastic material protects *surfaces* from perpendicular forces (*A*) but is easily displaced by shear (*B*). The efficacy of viscoelastic materials in *spatial* tactics depends little on the size of the drainage opening, so they can convert ocular chambers and subcompartments into secondary no-outflow systems that maintain their integrity over a given range of stresses (see Fig. 1.14c)

Criteria for the Selection of Viscous or Viscoelastic Materials

For the ophthalmic surgeon, viscous and viscoelastic materials have applications in surface tactics as well as spatial tactics. If they are to be used to maximum advantage, it is necessary to take their different physical properties into account even though both types of material may closely resemble each other in the resting state.

Viscous fluids are best for applications in **surface tactics**, since they form a thick, uniform protective coating when applied to surfaces (Fig. 1.19b). Viscoelastic materials form "plugs" which retain their shape well but protect only against the action of perpendicular forces (Fig. 1.19c).

In **spatial tactics**, viscous and viscoelastic materials are used to create secondary no-outflow systems. In this application viscous implants behave as fluids which, owing to their high outflow resistance, can pressurize a chamber with larger outflow openings than can pure watery fluids (Fig. 1.19b). Viscoelastic implants behave more as solids and can be used in either of two ways: to occupy a space completely ("visco-occupation") or simply to prevent outflow through orifices ("visco-blockade").

In **visco-blockade** (Fig. 1.20) the material is used simply to occlude and seal chamber outlets.[16] This prevents the drainage of fluid that should remain in the chamber to keep it pressurized. Visco-blockade also serves to prevent the undesired influx of extraneous material (blood, lens cortex, vitreous) into certain compartments of the eye.

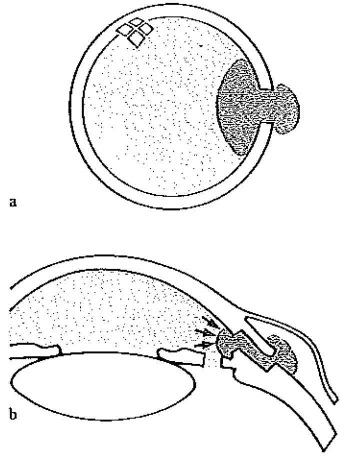

Fig. 1.20. Visco-blockade

a Principle: The drainage opening is occluded with a plug of viscoelastic material.

b Sample indication: Aqueous drainage through an antiglaucomatous fistula is blocked with the object of keeping the chamber formed in the early postoperative period. Aqueous circulation in the remaining parts of the chamber is not affected

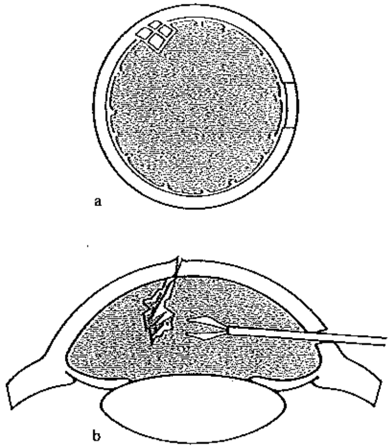

Fig. 1.21. Visco-occupation

a Principle: The entire chamber is filled with viscoelastic material.

b Sample indication: During the removal of a sharp-edged foreign body from the posterior corneal surface, visco-occupation protects the endothelium and lens capsule by stabilizing the chamber. Additionally, the material slows the movement of objects, making it easier to control the foreign body during the extraction

In **visco-occupation** (Fig. 1.21) the size of the chamber outlet has virtually no effect on the maintenance of pressure, because volume loss is resisted by forces within the viscoelastic material itself (Fig. 1.19c). Hence a space can be stabilized even in the presence of a large outflow opening. This is of particular interest in the subcompartments of the chambers, which cannot be effectively pressurized by any other means.

The stabilization of spaces by visco-occupation differs from stabilization by visco-blockade in the *rheologic situation* that prevails inside the space. Visco-blockade does not alter the environment within the chamber, whereas visco-occupation replaces the physiologic milieu in the chamber with a viscoelastic medium which retards the movement of instruments, implants, and mobile tissues.[17]

Side-Effects

The very properties that are advantageous when applied at the appropriate sites can be disadvantageous at other sites.

Visco-occupation of the wrong compartment in the eye can obliterate the portion of the intraocular volume that would otherwise be needed to expand the target compartment, making it impossible to achieve that expansion. *Visco-blockade* at the wrong sites can

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[16] Purely viscous substances are not well suited for this purpose. A substance viscous enough to effectively blockade a wound (that in Poiseuille's formula has a large r and a small L) cannot be injected through a cannula (that has a small r and a large L) unless it is pseudoplastic. Conversely, if a non-pseudoplastic substance can pass through an injection cannula, it could only occlude openings that are even narrower and longer than the cannula.

[17] The damping of movements (visco-tamponade) is an important protection against inadvertent movements of instruments and implants. But visco-tamponade can also have disadvantages such as the prevention of spontaneous iris movements. Further, it allows the transmission of shear forces from instruments with fast-moving parts (e.g., electrically powered trephines, vibrating knifes) to adjacent tissue (e.g., corneal endothelium). Visco-occupation can also prevent the uniform distribution of drugs injected intraoperatively (e.g., acetylcholine, alpha-chymotrypsin), making it necessary to flush the viscoelastic material from the target area before the drug is injected.

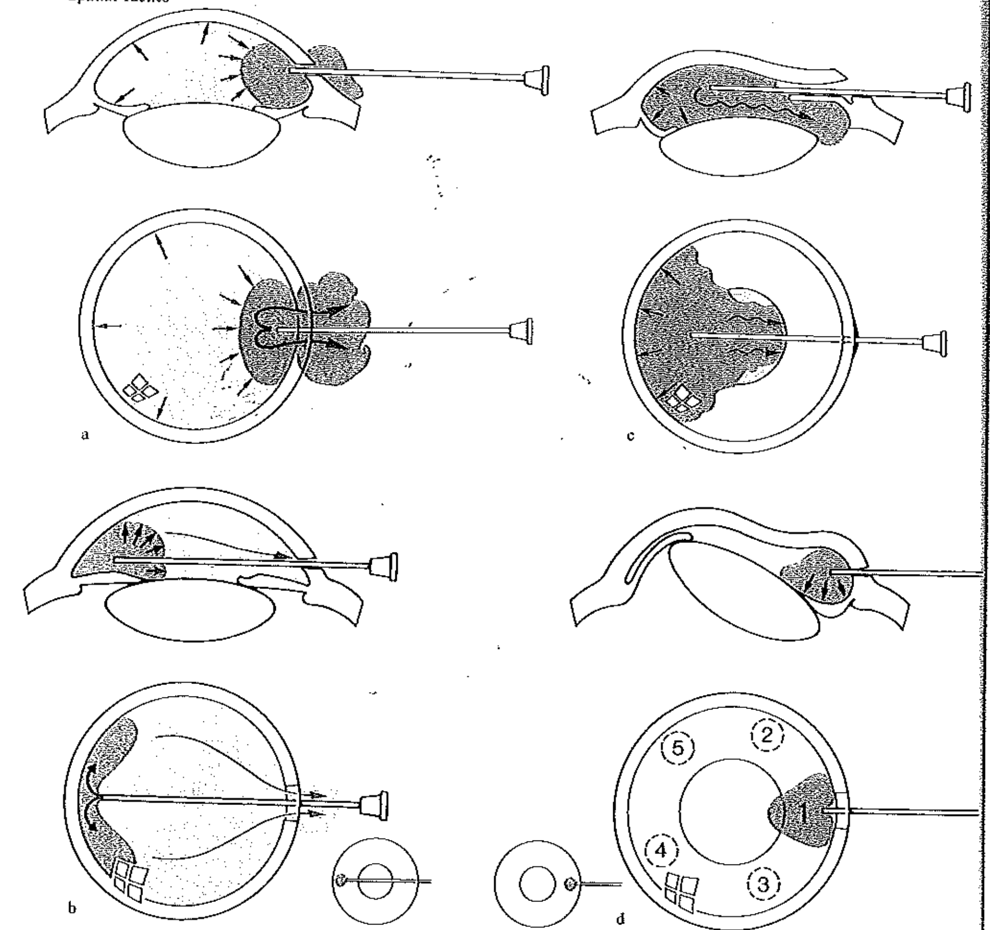


Fig. 1.22. Application of viscoelastic material: avoidance of side-effects when injecting into the anterior chamber through a small opening. Comparison of injections into an intact chamber (**a**, **b**) and a chamber that has been drained (**c**, **d**).
a, **c** Injection techniques that lead to side-effects.
b, **d** Injection techniques that avoid side-effects.

a If injection of the material is started at the access opening, a visco-blockade is formed. This prevents compensatory aqueous discharge, the chamber pressure rises, and the chamber cannot be filled with the material.

b If the injection is started well past the access opening, aqueous can leak, and the anterior chamber can be completely filled with viscoelastic material.

c There is no problem of compensatory aqueous discharge in an evacuated chamber. However, starting the injection opposite the opening may allow some material to get behind the ipsilateral iris. This occurs when the material presses the contralateral iris and lens downward, thus widening the access to the ipsilateral retroiridal space.

d Starting the injection just inside the opening pushes the iris onto the lens and keeps the material from entering the ipsilateral retroiridal space. Additional depots (2 to 5) are then placed about the circumference of the iris until the whole pupillary margin is blocked. At that time the rest of the anterior chamber may be filled.

Note: The two insets emphasize that injection into an aqueous-containing chamber (started opposite the access opening) is exactly opposite to the procedure used for an empty chamber (where injection is started at the opening)

obliterate passages that should remain clear in the context of the operative goal. This underscores the importance of placing viscoelastic materials *only at the sites where they are needed* and leaving them in place *only as long as they are needed.*

Application

The injection technique differs from that used for watery fluids, because the viscoelastic material must be placed precisely at the target site and nowhere else. In addition, the technique should take into consideration that the injection of viscoelastic implants always produces volume shifts in surrounding compartments. This leads to the following rules for the placement of viscoelastic materials:

- If compensatory volume shifts are desired (Fig. 1.22b), the pathways through which the shifts occur should *not* be obstructed.
- If compensatory shifts are not desired, the corresponding pathways *should* be obstructed (Figs. 1.22d, 1.23b).

Removal of Viscoelastic Materials

The localized removal of viscoelastic material is difficult. Material is most easily removed from a subcompartment if that subcompartment has a compliant, compressible wall (Fig. 1.24).

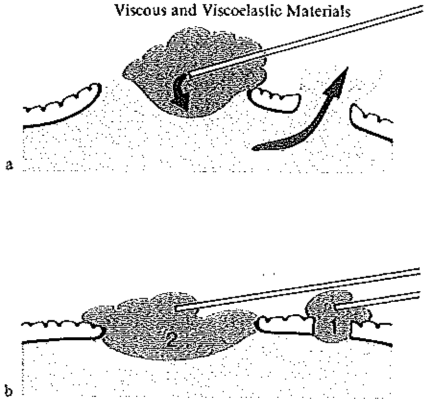


Fig. 1.23. Application of viscoelastic materials: avoidance of side-effects following intracapsular lens extraction. Volume shifts inside the chamber.

a Injecting into the pupil first can incite compensatory vitreous prolapse through the peripheral iridectomy. The prolapse, often unrecognized, may be injured by further maneuvers in the anterior chamber.

b This is avoided by occluding the iridectomy with viscoelastic material (*1*) before injecting into the pupil (*2*)

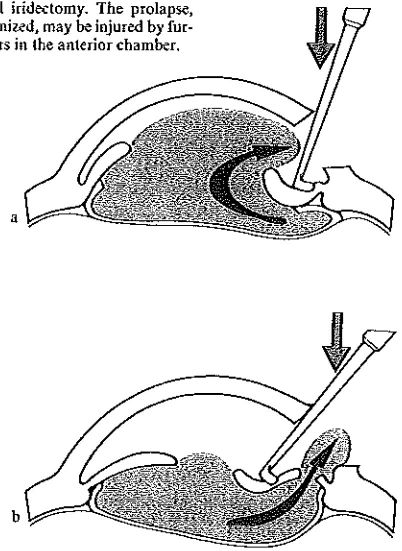


Fig. 1.24. Selective removal of viscoelastic material from a subcompartment (here: the retroiridal space). The anterior wall of the space (i.e., the iris) is pressed inward with a broad spatula to expel the viscoelastic material.
Note: Depression of the iris is maintained for a sufficient time to allow expulsion of the slow-flowing material.

a A large pupil provides an adequate outlet for the expulsion.

b If the pupil is small, a second, more favorably positioned outlet is created by iridectomy

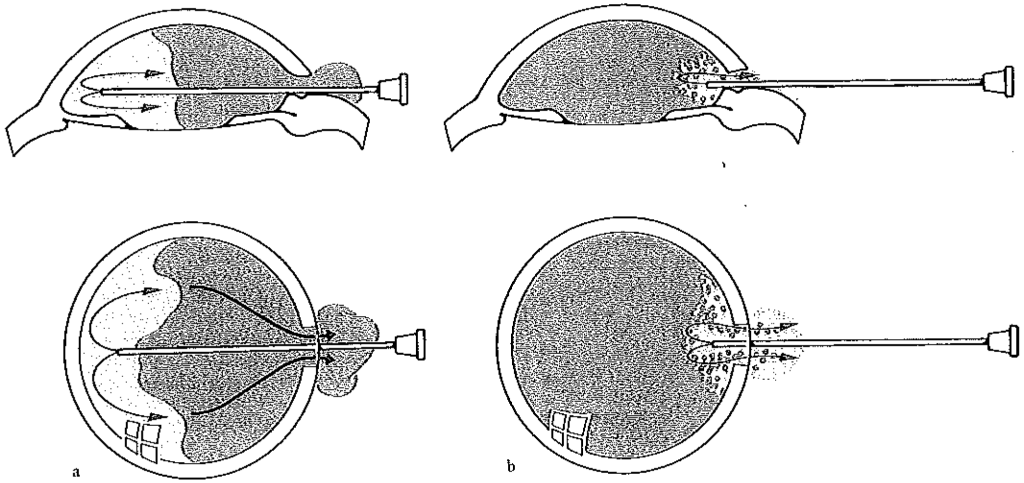


Fig. 1.25. **Evacuation of an entire chamber by irrigation with watery fluid**

a Evacuation in bulk. Watery fluid injected *opposite* to the access opening is kept inside the chamber by the viscoelastic material (visco-blockade). When the intraocular pressure rises sufficiently, the viscoelastic plug is expelled abruptly in one piece.

b Irrigation by dilution. The watery fluid is injected *just inside* the access opening. The material there is diluted and progressively removed with the irrigating stream

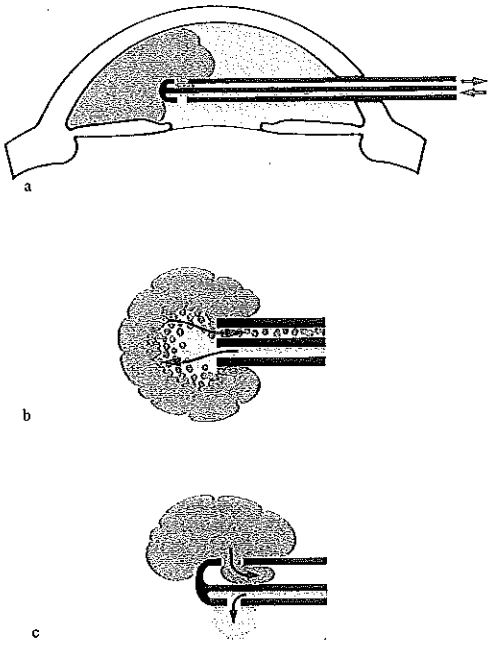


Fig. 1.26. **Evacuation by aspiration** ►

a Use of an infusion-aspiration cannula allows concomitant replacement of the aspirated volume.

b Aspiration of viscoelastic material by dilution. The infusion port should be as close to the aspiration port as possible (i.e., at the tip of the cannula) so that the diluted material is presented directly to the aspiration port.

c Aspiration in bulk. This technique requires an aspiration channel of large caliber due to the high flow resistance of the viscous material. The infusion and aspiration ports should be well separated; otherwise fluid of lower viscosity may be presented to the aspiration port and hinder the aspiration of more viscous material

Whole chambers can be evacuated by means of *irrigation* (Fig. 1.25) or *aspiration* (Fig. 1.26). In both procedures the material can be removed either *in bulk* (Figs. 1.25a, 1.26c) or by *dilution* (Figs. 1.25b, 1.26b).

In evacuation in bulk a large volume of material is extruded at one time. Thus, a sufficiently large inflow capacity is needed to compensate for the sudden volume loss. **Evacuation by dilution** is a more gradual process in which a continuous fluid stream is trained against the material to be evacuated. The pressure in the chamber remains relatively constant, and the chamber volume is easily controlled. On the other hand, the effect is not easily monitored since it becomes increasingly difficult to distinguish the diluted material from the watery ambient fluid as the evacuation proceeds.

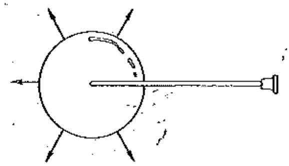
The slowest way to evacuate by dilution is to leave the material in the eye. Over time the material will be gradually diluted by aqueous and removed from the eye by natural mechanisms. This option is acceptable when there is reason to continue the effect of the viscoelastic material into the postoperative period.[18]

1.2.3 "Membranous" Implants (Bubbles)

When substances that are impermeable to watery fluids are injected into the eye, they form bubbles whose surface behaves like a membrane with respect to its watery environment.

Properties

Bubbles are essentially artificial pressure chambers. They are maintained by the **surface tension** produced by forces of attraction among the molecules in the adjacent media (Fig. 1.27). For a given composition of the bubble and the ambient medium, the surface tension of the bubble is inversely proportional to its size. Small bubbles have a higher tension than larger bubbles, and smaller coalesce with larger on contact (Fig. 1.34c). The largest "bubble" is the atmosphere, and when intraocular gas bubbles come in contact with the open air, they collapse.



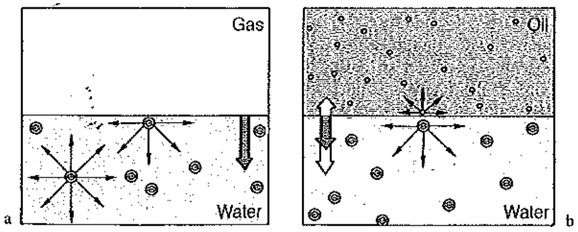


Fig. 1.27. **Development of surface tension at interfaces**

a At a water/gas interface, the forces of attraction among the water molecules cancel out within the water-filled volume. No such forces exist on the gas side of the interface, so the water molecules closest to the surface experience a net inward pull.

b At a water/oil interface, molecular attractions in the water are opposed by the (weaker) molecular attractions in the oil. Surface tension is the result of opposing force vectors. It is weaker at the water/oil interface than at the water/gas interface

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[18] Should evacuation of the material become necessary later (the main indication being a postoperative rise of intraocular pressure caused by visco-blockade of natural pathways for aqueous drainage), it can be released through a small keratotomy. Small, valve-like keratotomies are opened by depressing the lower wound margin (see Figs. 1.14c and 5.22b). The pressurized aqueous will expel the residual viscoelastic plug through the incision, whereupon the valve will close spontaneously.

To intraoperative spatial tactics mainly the surface properties of bubbles are relevant. Their contents are significant only in the way of determining the specific gravity of the bubble.[19]

The surface tension gives bubbles their *spherical shape*. Their tendency to retain that shape under the action of outside forces depends on the level of the surface tension.

Once in place within the eye, bubbles move and transmit forces without direct intervention by the surgeon. They do this under the action of *gravity*, whose effect is based on the difference between the specific gravities of the bubble contents and the medium.

Gravitational forces are opposed by friction, which is higher in bubbles injected into viscoelastic material than in a watery milieu. Accordingly, the surgeon can control the behavior of the bubble by appropriate selection of the bubble contents and ambient fluid. He can control the *direction* of bubble motion by using a light or heavy material,[20] and he can control the *speed* of its motion by providing a watery or viscous milieu.

The discussions that follow refer essentially to compressible air bubbles, although the specific conditions for incompressible silicone oil can be inferred from them.

The **size of the bubble** formed by injecting a given volume of air depends on the ambient pressure. Because air is compressible, a high ambient pressure in the chamber will result in smaller bubbles, and the volume of the bubble will change with the pressure in the chamber.[21] The maximum attainable size in any given situation is determined ultimately by the level of intraocular pressure that can be tolerated.

Indications for Bubbles

Bubbles, like viscoelastic materials, have two basic applications in spatial tactics: *outflow blockade* and *space occupation*.

For **outflow blockade**, bubbles produce an occlusive *seal* of leaks by virtue of their impermeability. The integrity of the seal depends on keeping the eye positioned so that the site to be occluded is uppermost (Fig. 1.28). Further the bubble must maintain sufficient contact with the margins of the opening that is to be occluded. The larger the bubble, the easier the blockade.

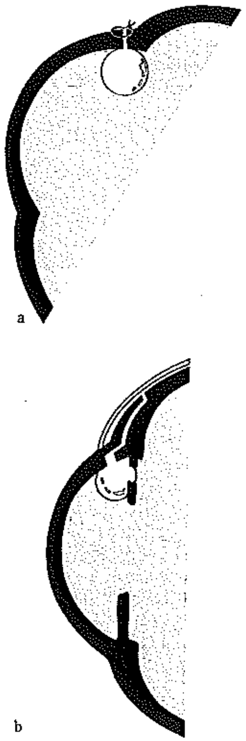

Fig. 1.28. **Outflow blockade with bubbles**

a Principle: The outlet is placed in a position where it will be occluded by the bubble, and it is maintained in that position.

b Example: Temporary blockade of aqueous drainage through an antiglaucomatous fistula, analogous to the situation in Fig. 1.20b. In contrast to a viscoelastic blockade, the effect depends on how well the necessary upright position can be maintained

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[19] On the other hand the chemical composition of the bubble contents is relevant to *postoperative* goals, for it determines the duration of placement (absorption time) and size progression of the bubble in the postoperative period. Gases that are soluble in blood are rapidly absorbed. Bubbles composed of exogenous gases (e.g., sulfur hexafluoride, perfluorocarbons) in which the partial pressure of blood gases is lower than in the environment tend to absorb oxygen, nitrogen, and carbon dioxide. Therefore bubbles of this type expand in the early postoperative period, and some time passes before the bubble diminishes in size. By mixing air and gases foreign to the blood in appropriate ways, the surgeon can have some control over postoperative bubble size. Bubbles composed of silicone oil may retain their original size indefinitely, though with passage of time they may become emulsified by the "stirring" action of tissue irregularities in the occupied compartment (e.g., vitreous strands).

[20] Gases and light silicone oil are lighter than aqueous, heavy silicone oils are heavier.

[21] Paradoxically, a bubble may become smaller as additional air is injected (thereby raising the chamber pressure). If a bubble is injected into a chamber that is under high pressure, it will enlarge postoperatively as the intraocular pressure falls due to natural aqueous drainage. This expansile effect is countered by the opposite and simultaneous effect of bubble absorption. It should be noted that the enlargement in this case is not due to the uptake of blood gases but relates to a fall of intraocular pressure.

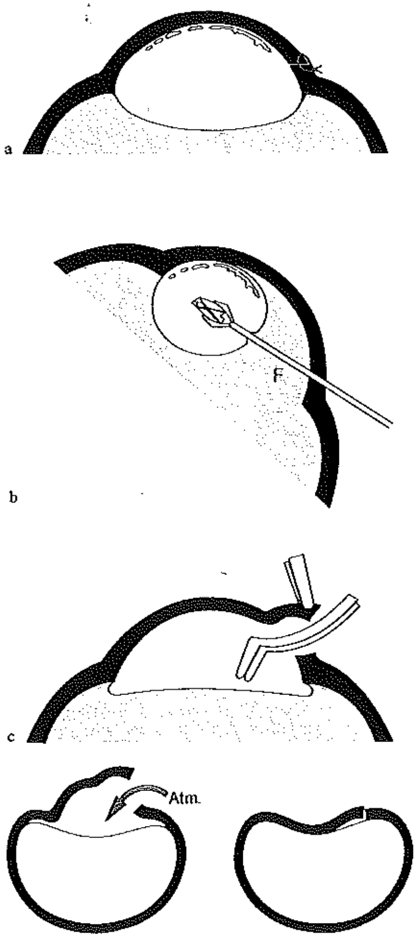

Fig. 1.29. **Space occupation with a bubble**

a A bubble completely filling a large compartment keeps the space free of tissue parts and fluids. If the surgeon now attempts to pass an instrument into the chamber, open air may come in contact with the bubble surface, causing the bubble to burst and collapse.

b When used to aid the removal of a foreign body from the anterior chamber, the air bubble must be positioned so that it is isolated from the incision by a fluid layer (F).[23] If the layer is a watery fluid, instruments designed for use in no-outflow systems should be used because of the low outflow resistance. If the layer is a viscoelastic material, bulkier instruments may be used.

c Air entering the anterior chamber through an open incision does not form a pressure chamber and is simply an extension of the outside environment. The presence of this air indicates that the vitreous pressure does not exceed atmospheric. As there is no danger that air will be expelled, manipulations may be performed freely.
Inset: When the anterior chamber pressure equals atmospheric, the presence or absence of a formed chamber depends not on relative pressures but on the intrinsic stiffness of the cornea. The situations on the left and right are identical in terms of pressure

For **space occupation**, bubbles can be used to occupy and *seal off spaces* that lack natural barriers against the influx of extraneous tissues and fluids (Fig. 1.29a).[22] The ambient pressure will determine whether manipulations can be performed within the occupied space. If the vitreous pressure does not exceed atmospheric, the surgeon can work in the occupied space while the incision is held open. In this case the air in the eye communicates with the air outside, which occupies the portion of the chamber that was previously evacuated (Fig. 1.29c). However, if the vitreous pressure does exceed atmospheric, the bubble must remain pressurized. Its integrity as a pressure chamber can be maintained during manipulations only if instruments are passed into it in a way that keeps it separate from the outside air. This is done by keeping the bubble surrounded by an adequate fluid layer. The outflow resistance of this fluid then limits the pressure at which the bubble can still be maintained.

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[22] *Example:* When the anterior hyaloid has been destroyed, an air bubble can be injected to define a space that is entirely devoid of vitreous. The bubble surface acts as an artificial hyaloid, enabling the surgeon to develop an effective counterpressure in the anterior chamber to the vitreous cavity.

[23] In contrast to viscoelastic materials (Fig. 1.21), air is suitable for space occupation only if the globe can be appropriately rotated.

Side-Effects of Bubbles

During operations the major problem with bubbles is their poor reliability as spatial stabilizers. If manipulations bring their surface into contact with the open air, they rupture. In this case their surface tension and extremely low outflow resistance allow a large volume to escape the chamber so rapidly that collapse is inevitable; the lost air cannot be replaced with an equal fluid volume at the same speed. Consequently, bubbles provide reliable space-tactical instruments only in situations where they can be kept isolated from the environment by *suitable positioning* (Fig. 1.29b).

Postoperatively, bubbles may obstruct paths that should remain open for aqueous drainage, causing a rise of intraocular pressure. This problem is avoided by *repositioning the globe* (or the patient) as required (Figs. 1.30 and 1.31). If the necessary position cannot be maintained around the clock, *additional drainage openings* can be created to provide for adequate aqueous flow drainage (Fig. 1.32).

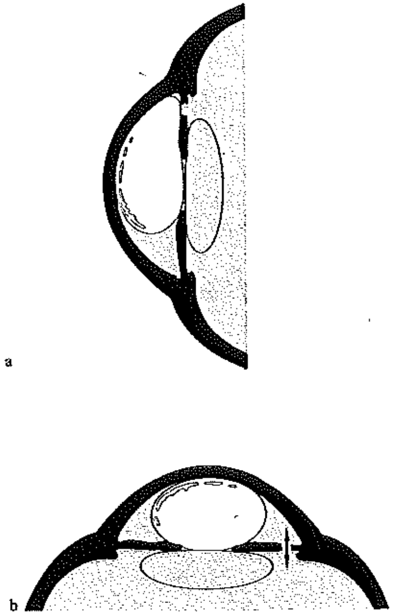

Fig. 1.30. **Obstruction of aqueous circulation by an air bubble**

a With the patient in an upright position, the bubble occludes the superior basal iridectomy. The possibility of aqueous circulation through the pupil depends on the pupil size.

b If the pupil is too small, the basal iridectomy can be uncovered by moving the patient to a supine position

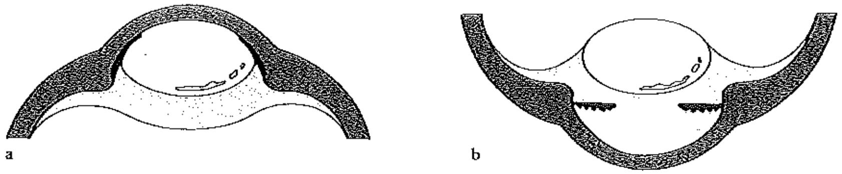

Fig. 1.31. **Obstruction of aqueous circulation in the aphakic eye by an air bubble in the wrong compartment**

a Air trapped behind the iris in an aphakic eye blocks the pupil and obliterates the anterior chamber.

b Moving the patient to the prone position removes the bubble from the iris and restores circulation through the pupil

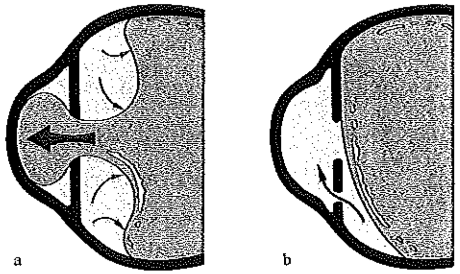

Fig. 1.32. **Obstruction of aqueous circulation in the aphakic, vitrectomized eye: vitreous replacement with silicone oil**

a A silicone bubble can obstruct the pupil in the aphakic eye. Aqueous collects behind the iris, forcing the silicone oil through the pupil towards the cornea.

b Aqueous circulation is restored by iridectomy. The silicone bubble returns to a spherical shape and remains behind the pupil. The iridectomy is placed inferiorly for light silicone oil and superiorly for heavy oil

Application of Bubbles

The technique of bubble injection into the eye affects the size of the bubble but does not determine its **site of action.** The latter depends on the migratory tendency of the bubble, i.e., on the position of the globe (Fig. 1.33) and on the pattern of flow resistances inside the chamber (Fig. 1.34). Accordingly, the site of action of bubbles can be influenced by repositioning the eye and eliminating resistances.[24]

The **size of bubbles** can be controlled by the application technique, at least within the limits imposed by the intraocular pressure.[25] The *choice of the injection site* affects the attainable size in the sense that the bubble may collapse if it can reach the atmosphere at the access opening (Fig. 1.33). The location of the access opening has no effect on bubble size only if the opening is completely sealed around the injection cannula (see Fig. 1.12a), or if the pressure in the chamber does not exceed atmospheric (see Fig. 1.29c).

The *injection technique* influences bubble size in that air injected forcibly is likely to form multiple small bubbles instead of a single large one (Fig. 1.35a). A *large bubble* is formed by advancing the cannula to the center of the emerging bubble and then inflating it gradually by slow, steady pressure on the plunger (Fig. 1.35b, c). Thus, in contrast to the injection of watery fluids, where the cannula remains near the access opening, an air-injecting cannula should be inserted well into the chamber. The tip should be placed initially at a site where sufficient space is available for the desired bubble size (this does not coincide with the site of action!) and then advanced into the bubble itself.

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[24] Besides the problems shown in Fig. 1.34 associated with the presence of viscoelastic material in a watery milieu, nonhomogeneities can result from the entry of vitreous into the anterior chamber. This can lead to the undesired spread of air bubbles into the vitreous cavity.

[25] If the bubble cannot attain a sufficient size at the tolerable intraocular pressure, the only recourse is first to lower the pressure by the drainage of chamber fluid.

Fig. 1.33. **Injection of bubbles into a watery milieu** ►

a If injection is attempted from a high point, the air is in contact with the atmosphere initially, and a bubble cannot be formed – unless the chamber pressure does not exceed atmospheric.

b A bubble injected from a low point will rise from there to the highest point. Air can be injected until the bubble reaches the access site, i.e., downward expansion of the bubble is limited by the position of the access opening

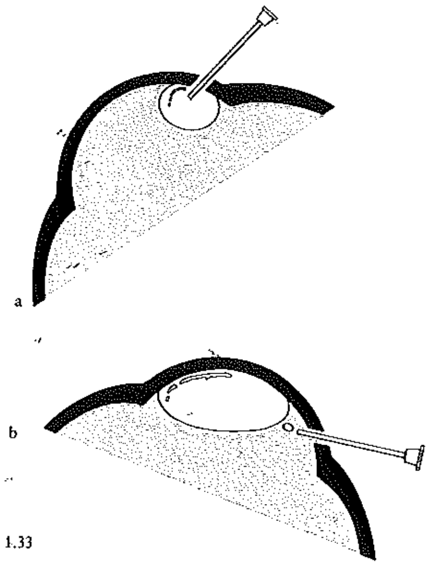

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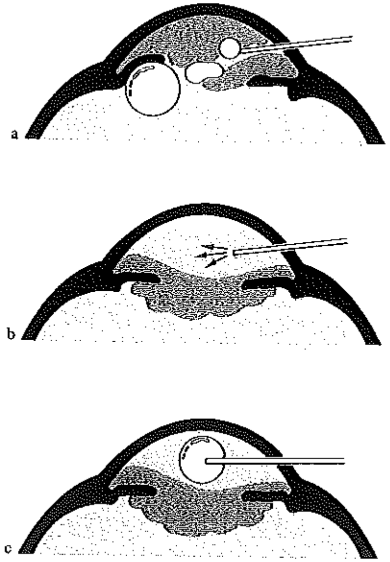
Fig. 1.34. **Injection of bubbles into a nonhomogeneous milieu (irregular distribution of watery and viscoelastic material)**

a Air bubbles injected into a nonhomogeneous milieu follow paths of least resistance. Passing along watery "tracks," they may become trapped behind the iris or behind an implant.

b Preparation of a homogeneous milieu in the target area (here, below the corneal apex). Undesired spread is prevented by injecting watery fluid into the target area to create a localized homogeneous milieu.

c Air is then injected into the homogenized area



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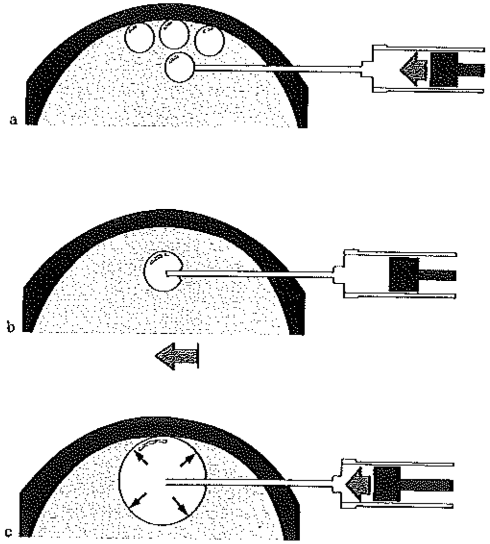

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Fig. 1.35. **Technique of air bubble injection**

a If the cannula tip is held stationary while injecting air, the bubble will detach and rise as soon as it has sufficient buoyancy, and multiple small bubbles will form.

b To obtain a single large bubble, the cannula tip must be advanced into the bubble during the injection.

c The bubble will gradually expand as air is injected[26]

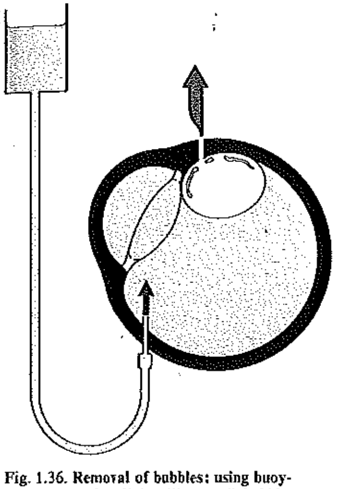

Fig. 1.36. **Removal of bubbles: using buoyancy to expel a light silicone oil bubble.** The globe is rotated until the outlet is uppermost. Fluid is infused at another site to replace the lost volume and maintain the chamber pressure

Removal of Bubbles

The simplest way of removing bubbles is to position the access opening so that the bubble is expelled by its own **buoyancy** (Fig. 1.36). This method is excellent for silicone oil bubbles, which, because of their viscosity, move slowly and allow ample time for volume replacement with fluid to prevent ocular collapse. Gas bubbles are expelled too rapidly for this type of volume replacement, and the suitability of buoyancy expulsion for gas bubbles depends on whether an abrupt volume loss of that size can be tolerated.

The **needle aspiration** of bubbles can be more accurately controlled.[27] If the opening of the cannula is held close to the bubble surface, fluid may be aspirated rather than gas. The cannula should be inserted to the center of the bubble to ensure that its contents are aspirated (Fig. 1.37c). Small bubbles that are displaced by the needle rather than penetrated because of their high surface tension can be engaged by injecting a large adjacent bubble (Fig. 1.37a) and allowing the bubbles to coalesce before aspirating (Fig. 1.37b).

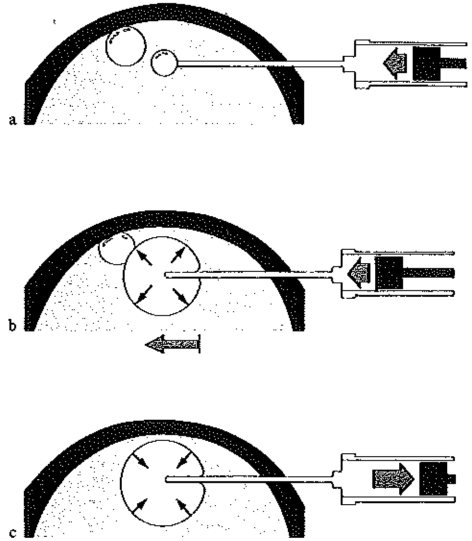

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Fig. 1.37. **Aspiration of air bubbles**

a Small air bubbles are "captured" by injecting a second, contiguous bubble. (It is paradoxical that the aspiration of air begins with an injection!)

b The second bubble is enlarged by advancing the cannula tip to its center (see Fig. 1.35c). When the second bubble has attained sufficient size, both bubbles will coalesce.

c Finally the cannula is advanced to the center of the single large bubble. The cannula should be kept at the center of the bubble until the aspiration is completed

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[26] Note: A slow injection rate is essential. Rapid injection may produce multiple small bubbles, especially if the surrounding aqueous contains emulsifying proteins. As stated earlier, small bubbles have a higher surface tension, so they require more energy for their production than large bubbles.

[27] This technique may cause problems with silicone oil bubbles because of their high viscosity (see Fig. 1.15b).

1.3 The Field of Spatial Tactics

1.3.1 The Pressure Chamber of the Globe

The globe of the eye is a sphere (Fig. 1.38), so any force that deforms the globe will reduce its volume and raise its internal pressure (see Fig. 1.41). Very high pressures may be reached owing to the mechanical strength of the cornea and sclera. In the operated eye, the attainable pressure level depends on the quality of the wound closure.

Because of the very high outflow resistance through natural aqueous drainage pathways, some time is required for an increased pressure to return to its initial level and for any volume loss to occur (see Fig. 1.7). Acute forces do no more than raise the intraocular pressure, while forces of longer duration lead ultimately to deformation of the globe.[28]

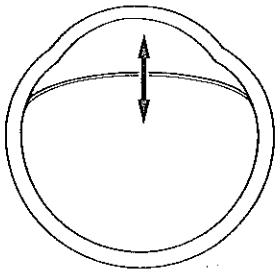

Fig. 1.38. **The pressure chambers of the eye.** The pressure chamber of the overall globe is approximately spherical. The diaphragm subdivides it into two smaller pressure chambers that are nonspherical. Besides anatomic factors, the position of the diaphragm depends on the pressure differential between the two chambers. When the anterior chamber is breached, the vitreous forms the only pressure chamber, and vice versa

1.3.2 The Pressure Chamber of the Vitreous

When the anterior chamber is opened and communicates freely with the outside air (i.e., anterior chamber pressure = atmospheric pressure), the pressure chamber of the vitreous humor remains. This differs from the overall pressure chamber of the globe in its shape and wall strength. Because the vitreous pressure chamber is *not a sphere*, external forces will not necessarily reduce its volume or raise its pressure. The anterior wall of the vitreous chamber, the diaphragm, is thinner and more distensible than the cornea and sclera, and it may be weakened further in the course of operative maneuvers.

The **diaphragm** consists of several membranes arranged in sequential layers (Fig. 1.39). If one of these membranes is perforated during the course of an operation, it is no longer part of the pressure chamber,[29] and the remaining wall is weakened. The innermost layer of the diaphragm is the anterior hyaloid membrane. Once this membrane is breached, the vitreous ceases to form a pressure chamber (Fig. 1.39d).

The distensibility of the diaphragm makes it a useful guide for evaluating the relative pressures in the vitreous chamber and anterior chamber. This forms the basis for the **semiology of the diaphragm** (Fig. 1.40). As long as the diaphragm remains in its **anatomic position**, the pressure in the vitreous chamber equals that in the anterior chamber. Thus, when the anterior chamber is opened, the diaphragm will remain stationary only if the vitreous pressure is zero (i.e., equal to atmospheric). **Anterior movement of the diaphragm** signifies that the vitreous pressure exceeds the pressure in the anterior chamber. The difference may result from negative pressure in the anterior chamber (capillary attraction of the diaphragm to the posterior corneal surface), in which case the pressure in the vitreous may still be low (Fig. 1.40a).[30] But if the difference results from elevated pressure in the vitreous chamber, the surge of the diaphragm is not limited to the anterior chamber, and intraocular contents may even be exteriorized (Fig. 1.40c).

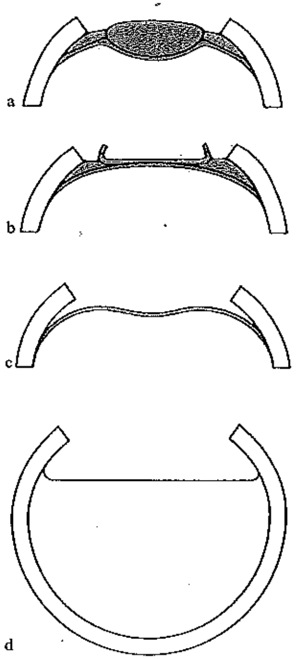

Fig. 1.39. **The vitreous chamber: effects of surgical measures on its anterior wall (the diaphragm)**

a When the anterior chamber is opened, the anterior wall of the vitreous is formed by the lenticulozonular membrane, consisting of the weak, distensible zonule and the rigid, stable lens.

b When the anterior lens capsule is opened, the diaphragm consists of the zonulocapsular membrane, which contains no rigid parts.

c If the zonulocapsular membrane is breached, the vitreous chamber is bounded only by the very delicate anterior hyaloid membrane.

d With rupture of the anterior hyaloid, the vitreous loses its containment and ceases to exist as a pressure chamber

Recession of the diaphragm signifies a fall of pressure in the vitreous space. If not caused by surgical manipulation, a recession of the iris should raise suspicion of a ruptured anterior hyaloid with prolapse of free vitreous into the anterior chamber (Fig. 1.40e).

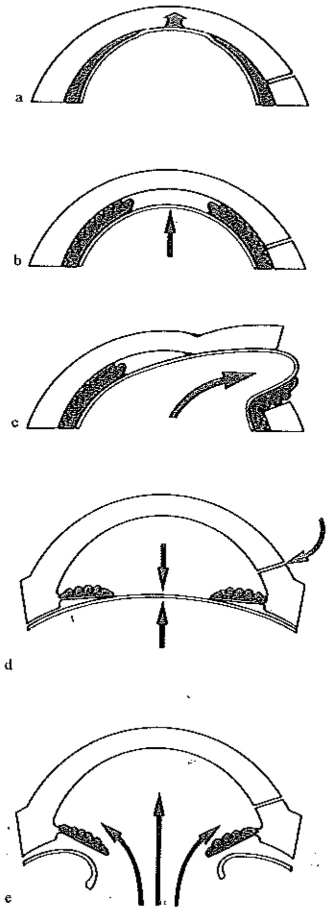

Fig. 1.40. **Semiology of the diaphragm.** Indicators of vitreous pressure with an open anterior chamber.

a "Negative pressure" prevails in the anterior chamber when the diaphragm is pulled forward by capillary attraction. The iris trabeculae are pressed flat against the inner corneal surface, and their normal contour is obliterated.

b With a positive pressure in the vitreous chamber, the anterior chamber discharges most of its contents, but the iris contour is preserved, and some chamber volume is retained at the pupil. Iris flattening as in **a** is very unusual in case of a non watertight chamber, and a further rise in vitreous pressure would most likely produce the situation in **c**.

c Vitreous prolapse: If the vitreous pressure becomes high enough to overcome the elastic resistance of the cornea, the diaphragm will protrude outward through the wound.

d When the anterior chamber is repressurized to a level matching the vitreous pressure (by effective wound closure and fluid infusion), the diaphragm returns to its anatomic position.

e A fall of vitreous pressure is manifested by recession of the diaphragm. This occurs when the pressure chamber of the vitreous is destroyed, and signifies perforation of the anterior hyaloid

1.3.3 Effect of Deforming Forces on the Pressure Chambers of the Eye

Any deformation of the **entire globe** will raise the intraocular pressure (Fig. 1.41). Only the magnitude of the applied forces is significant; the site at which the forces are applied is immaterial. But for the **pressure chamber of the vitreous**, the site of force application is an important factor. Deformations *above* the diaphragm do not affect the vitreous chamber or its pressure. Deformations *at the level* of attachment of the diaphragm reduce its area and relax the membranes, which then may undergo significant displacement or prolapse.[31] Deformations *below* the attachment of the diaphragm do not change its area, and the diaphragm remains tense. The pressure in the chamber can rise and stretch the membranes, possi-

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[28] Permanent deformations like those produced in buckling retinal detachment operations cause a pressure rise immediately after the sutures are tightened, posing a threat to blood circulation in the eye. If decompression by natural drainage is too slow, lower-resistance drainage must be established by surgical means (e.g., puncture of the anterior chamber).

[29] Note: The iris, being perforated by the pupil, does not actually contribute to the anterior wall of the vitreous chamber. However, its opacity makes it an important indicator of the behavior of the transparent membranes of the true diaphragm.

[30] Besides referral to morphologic signs (Fig. 1.40a, b), negative pressure in the anterior chamber can be differentiated from a high vitreous pressure by placing a few drops of watery fluid on the wound margin. With a negative pressure the fluid will be sucked into the wound, and the diaphragm will recede. With a high vitreous pressure this will not occur, and it is necessary to repressurize the anterior chamber by effective wound closure so that its internal pressure can again be increased to the level of the vitreous pressure (Fig. 1.40d).

[31] Iris prolapse is based on different mechanisms, since the iris is not part of the diaphragm (see footnote [29], p. 28). A prolapsing iris first flattens against the wall of the globe, for a time acting as a valve and restoring the pressure chamber. A further pressure rise will cause the iris (the least stable part of the wall) to bulge and protrude through the corneal opening (see also Fig. 7.3c). Iris prolapse thus depends on the pressure in the entire globe, not just in the vitreous chamber, and can be produced even by deformations above the diaphragm.

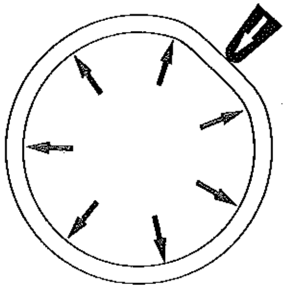

Fig. 1.41. **Deformation of the globe.** A sphere has the smallest possible ratio of surface area to volume. Any change in its shape will reduce the volume. No matter where the deforming forces are applied, the effect is the same (Pascal's law)

bly to the point of prolapse or even rupture (Fig. 1.42).[32]

Even in the **breached vitreous chamber**, the effects of a deforming force depend on its site of application. Since the pressure in the vitreous can no longer rise, the only effect of applied forces is to deform the vitreous body. For a given volume displacement, the rise in the fluid level is greatest when the deforming force is applied at the level of the vitreous face, thereby reducing its surface area (Fig. 1.43).

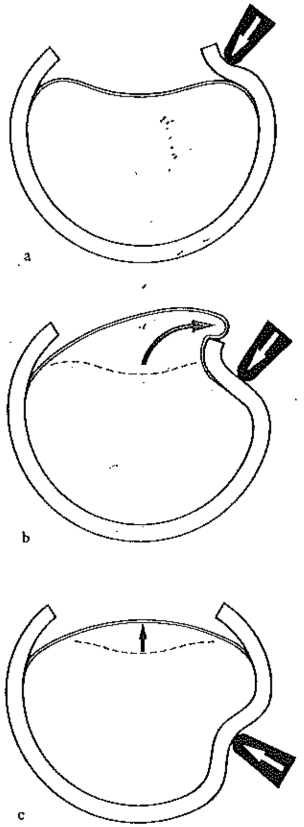

Fig. 1.42. **Deformations of the vitreous chamber.** The effect of deforming forces on the vitreous body depends on the site of application.

a Deformation of the globe anterior to the diaphragm has no effect on the pressure chamber.

b Deformations of the globe at the level of the diaphragm relax the membranes and can cause significant vitreous displacement without raising the vitreous pressure.

c Deformations posterior to the diaphragm tense the membranes and raise the vitreous pressure

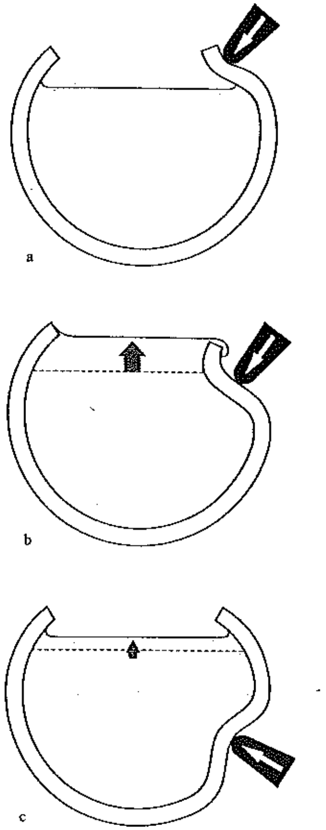

Fig. 1.43. **Deformation effects in the breached pressure chamber of the vitreous.** Here too, the effect of the deforming force depends on the site of the deformation.

a Deformations of the globe above the vitreous face do not affect its level.

b Deformations at the level of the vitreous face reduce its surface area. The fluid face rises markedly in relation to the displaced volume, and prolapse occurs.

c Deformations below the vitreous face do not change its surface area, so the fluid face rises less than in **b**

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[32] The two mechanisms of prolapse differ fundamentally. The prolapse of Fig. 1.42b is a purely anatomic displacement caused by geometric factors at low pressure; the membranes may remain intact and are reducible when the cause has been removed. The prolapse mechanism of Fig. 1.42c is caused by increased pressure, is associated with stretching of the membranes, and poses significant risk of membrane rupture.

1.3.4 Deformations Caused by External Forces

Mechanisms

Every external force acting on the globe has two effects: *displacement* of the globe within the orbit and *deformation* of the globe itself. Which effect is predominant is a matter of resistances. When there is high resistance to ocular displacement, an applied force will tend to deform the globe rather than displace it. Conversely, the globe will undergo little or no deformation if it is mobile enough to be pushed aside by an applied force, i.e., if its passive mobility is high. The **inward mobility** of the globe is determined chiefly by the resistance of the orbital cushion (Fig. 1.44a). Its **outward mobility** is limited by the resistance of the extraocular muscles and of any mechanical barriers such as lid retractors, tense eyelids, etc. (Fig. 1.44b). **Movements of the globe about its center of rotation** meet minimal resistance because the eye and orbit, much like a spheroidal joint, are designed for maximum freedom of rotation (Fig. 1.44c).

External forces will deform the globe only if its passive mobility is restricted.[33] Unrestricted passive mobility, then, offers the best protection against unplanned deformations of the globe. On the other hand, excessive mobility is clearly disadvantageous when it interferes with planned surgical actions. Thus, unrestricted passive mobility is appropriate as a general safety strategy for most of the operation, but for *specific manipulations* it may be necessary to suspend passive mobility by temporary fixation of the globe.

In the immobilized globe, the **direction of application** of the force vectors determines the effect on the ocular pressure chambers. Maximum deformation is produced by *perpendicular* vector components and minimum deformation by *tangential* vector components (components parallel to the ocular surface). Thus, manipulations with perpendicular vectors are appropriate only when deformation of the globe is intended (Fig. 1.45a). Otherwise they should be strictly avoided and replaced with techniques that involve just the application of tangential forces (Fig. 1.45b).

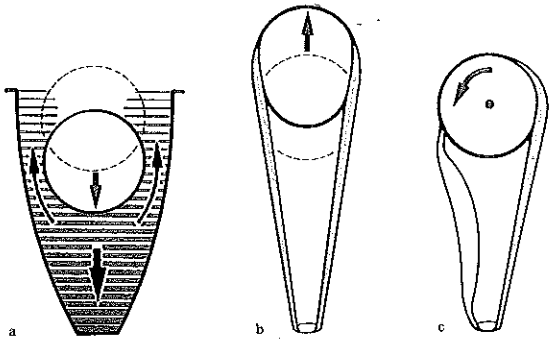

Fig. 1.44. **Factors influencing the passive mobility of the globe**

a The resistance to *inward* movement of the globe depends on the compliance of the orbital cushion.

b Resistance to *outward* movement of the globe depends on the distensibility of the ocular muscles and other adnexa.

c Movements of the globe about its *center of rotation* encounter minimal resistance and actually are limited only in pathologic states (e.g., abnormal muscle tension, adnexal scarring)

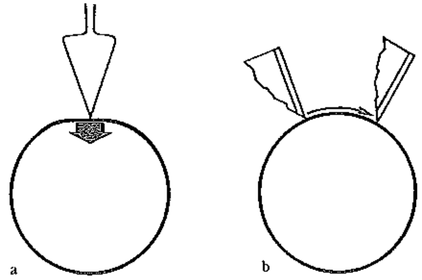

Fig. 1.45. **Effects of deforming forces on the immobilized globe**

a Perpendicular vector components (directed toward the center of the globe) cause maximal deformation of the ocular chambers.

b Tangential vector components (parallel to the ocular surface) cause minimal deformation

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[33] Examples: Passive ocular mobility may be reduced by increased orbital resistance due to infiltration with anesthetic or blood, or by a high muscle tone.

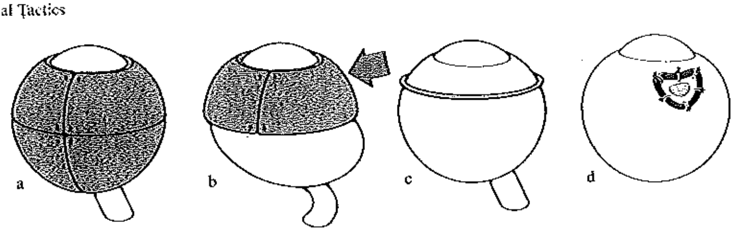

Fig. 1.46. Stabilization of the chambers by corset systems

a Total protection can be achieved only by the complete encasement of the eye – obviously an impractical solution.

b Partial corset systems protect against locally applied forces. But if the forces displace the corset as a whole, the corset system itself can be a source of deformation, the effect depending on the width of the system.

c Maximum reduction of the system width leads to a simple stabilizing ring.

d Specially configured rings for local use protect specific areas from deformation (e.g., the margins of excisions) but do not protect entire chambers. As static fixation instruments, their application lies more in the area of tissue tactics than spatial tactics

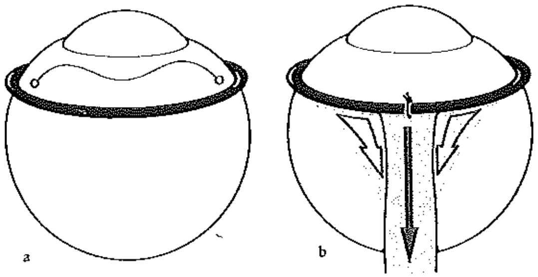

Fig. 1.47. Stabilization of the vitreous chamber

a A ring fixed to the globe at the level of the diaphragm attachment stabilizes against deformations that cause the greatest shifts of intraocular tissue (see also Figs. 1.42, 1.43).

b If the ring is attached at the insertions of the extraocular muscles, the force of the muscles is distributed over a larger and more stable area, so their deforming action is reduced

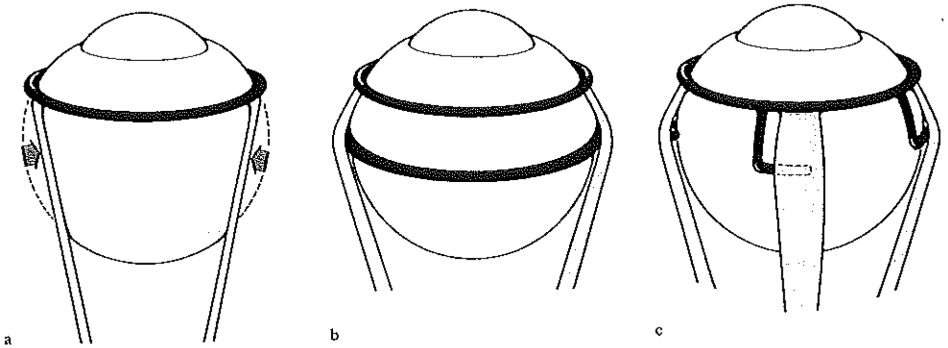

Fig. 1.48. Protection of the equatorial zone

a Indentation of the equatorial region by contraction of the extraocular muscles.

b The equator is protected by placement of a second ring.

c In a simpler system having the same effective width (analogous to Fig. 1.46b), the primary ring carries outrigger extensions that slip beneath the muscle insertions

Protection from External Deforming Forces

External corset systems suitable for practical use are always a *compromise* (Fig. 1.46). In principle, systems with a large contact area would be most effective in protecting the eye from compression[34], but a large contact area is potentially destructive when forces become large enough to displace the entire corset (Fig. 1.46b). Reducing the contact area to a minimum leads to a simple ring configuration.

Stabilizing rings are most effective when they are used to protect the *areas* whose deformation would be most hazardous from the *forces* most likely to cause such deformations. Rings attached at *muscular insertions* accomplish both goals. They reduce the pressure caused by unforeseen muscular tension (Fig. 1.47b) while also stabilizing the area of attachment of the diaphragm, whose deformation is known to cause the greatest clinical problems (Fig. 1.47a).

Of course such rings cannot prevent indentation of the globe by the eye muscles at the equator, where the ocular diameter exceeds the ring diameter. A *second stabilizing ring* would be needed to prevent equatorial compression by muscle tension (Fig. 1.48).[35]

Internal stabilization can be accomplished with viscoelastic materials, which offer resistance to deforming forces by virtue of their elasticity.

1.3.5 Deformation by Hinge Folds

The mechanism for opening a flap-shaped incision involves *rotation of the flap* about an axis connecting the ends of the incision (Fig. 1.49). This rotation produces a *hinge fold*, which can deform the vitreous chamber (Fig. 1.53).

The formation of a fold on a sphere is associated with complex tissue displacements (Fig. 1.50). The most important of these effects can be characterized as "intramural alignment" and "extramural alignment."

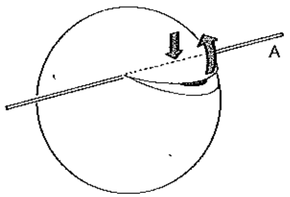

Fig. 1.49. Formation of a hinge fold. Any incision that does not follow the path of a great circle produces a flap that can be elevated to open the wound. The flap rotates on an imaginary "hinge axis" (*A*) connecting the ends of the incision. If the flap is turned upward, the domed ocular surface along the hinge axis becomes flattened, and a fold is produced

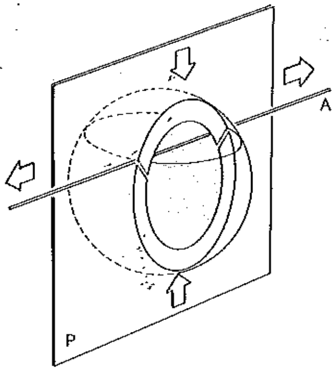

Fig. 1.50. Analysis of fold formation. When a flap is raised, the axis of rotation must be straight even though the ocular wall is spherical. To form the axis, all parts of the ocular wall lying above the straight line connecting the ends of the incision must move onto that straight line (the imaginary hinge axis). Any change in the spherical contour of the globe has far-reaching effects. The most important of these effects occur on the vertical plane (*P*) through the axis (ends of the flap-shaped wound). This plane is indicated in subsequent figures, which illustrate the surgically relevant changes in detail

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[34] Pressure = force per unit surface area.

[35] The risk-to-benefit ratio of a two-ring system is not very favorable, since deformations in the equatorial region produce a relatively minor effect (see Fig. 1.42c) that can be managed with an appropriate margin of deformation (q.v.). Conversely, a two ring system, especially with connected rings, behaves like the partial corset in Fig. 1.46b.

Intramural alignment refers to the *rotation of the wound surfaces* in the direction of the hinge as the flap is raised (Fig. 1.51). This rotation is accompanied by stretching and compression of the tissues encompassed by the incision, setting up a resistance whose magnitude depends on the angle between the wound surface and the hinge line.

Extramural alignment is the *flattening of the ocular dome* that occurs over the hinge axis. This causes the ends of the wound to move apart, the degree of separation depending on the height on the dome above the hinge axis (Fig. 1.52). If this diverging effect is opposed by a high resistance (due, for example, to the stiffening of the tissue during intramural alignment), raising the flap will cause an *inversion of the ocular dome* with a correspondingly greater mass effect upon the vitreous (Fig. 1.52d).

The effects of a hinge fold on vitreous pressure depend on the *position of the hinge fold* relative to the vitreous chamber. With *corneal* folds, the anterior chamber provides a certain spatial reserve, and the position of the hinge axis in relation to the diaphragm will determine whether a danger is posed to the vitreous (Fig. 1.53).[36] *Scleral* flaps always affect the vitreous chamber, and even the slightest infolding will elevate the vitreous pressure.

The problems of hinge folds can be reduced by an appropriate incision technique. Thus, *intramural alignment* is influenced by the *profile* of the incision, which can be modified so that the primary angle between the wound surface and hinge line is zero (Fig. 1.51b, d). *Extramural alignment* is influenced by the *shape of the flap*, which can be tailored to minimize the height of the ocular dome (Figs. 1.54, 1.55).

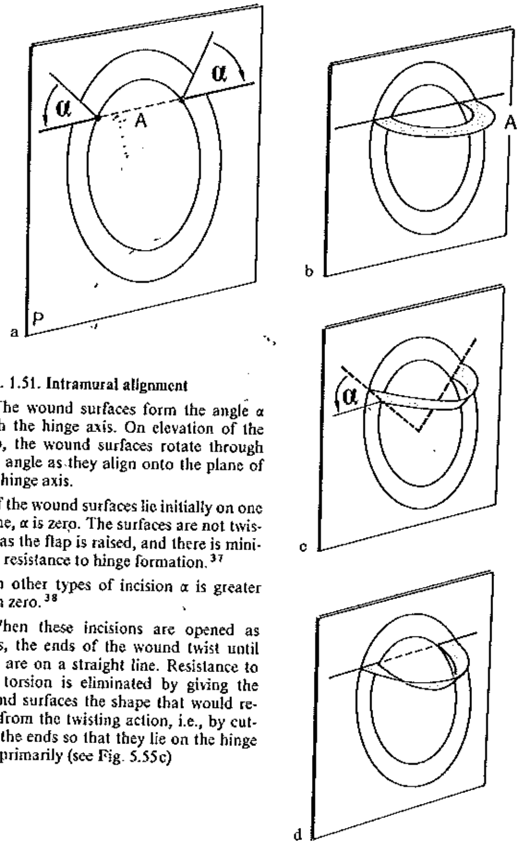

Fig. 1.51. **Intramural alignment**

a The wound surfaces form the angle α with the hinge axis. On elevation of the flap, the wound surfaces rotate through this angle as they align onto the plane of the hinge axis.

b If the wound surfaces lie initially on one plane, α is zero. The surfaces are not twisted as the flap is raised, and there is minimal resistance to hinge formation.[37]

c In other types of incision α is greater than zero.[38]

d When these incisions are opened as flaps, the ends of the wound twist until they are on a straight line. Resistance to this torsion is eliminated by giving the wound surfaces the shape that would result from the twisting action, i.e., by cutting the ends so that they lie on the hinge axis primarily (see Fig. 5.55c)

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[36] With a shallow anterior chamber, raising a flap causes an immediate rise of vitreous pressure. Even the initial attempt to raise the flap may incite vitreous prolapse.

[37] For example: keratome and cataract knife incisions have surfaces that lie *primarily* on the hinge line (see p. 164–168).

[38] Arbitrary angles can be made when cutting with scissors.

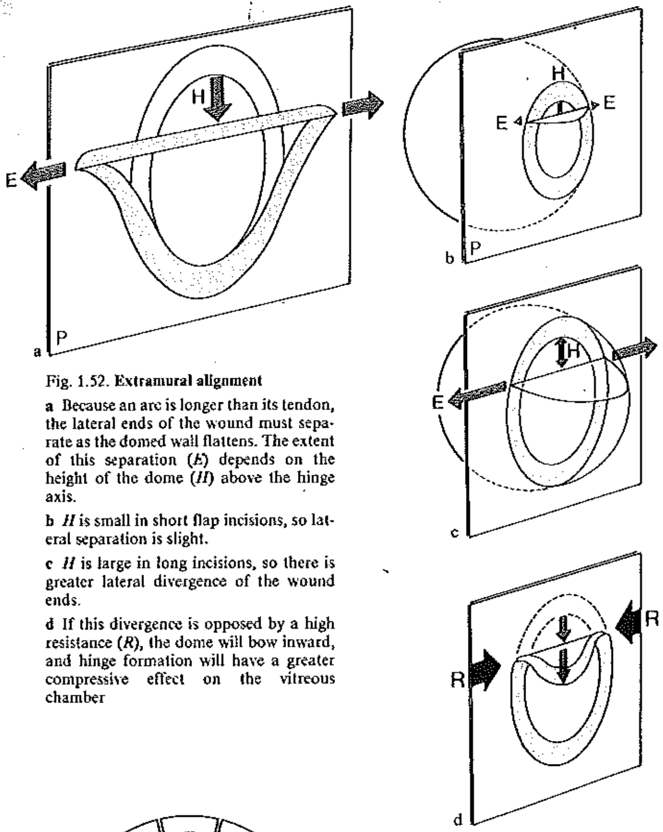


Fig. 1.52. **Extramural alignment**

a Because an arc is longer than its tendon, the lateral ends of the wound must separate as the domed wall flattens. The extent of this separation (*E*) depends on the height of the dome (*H*) above the hinge axis.

b *H* is small in short flap incisions, so lateral separation is slight.

c *H* is large in long incisions, so there is greater lateral divergence of the wound ends.

d If this divergence is opposed by a high resistance (*R*), the dome will bow inward, and hinge formation will have a greater compressive effect on the vitreous chamber

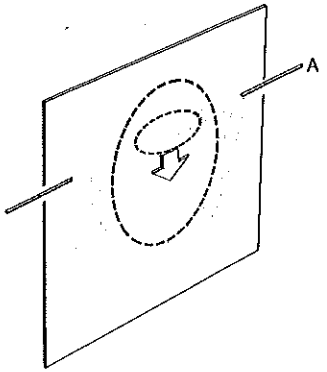
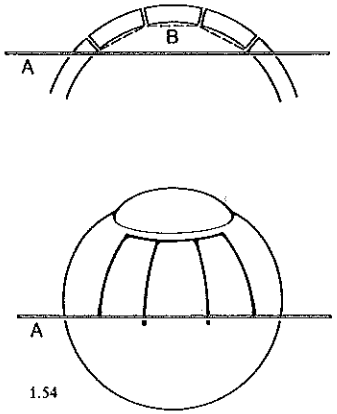
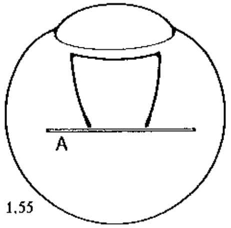


Fig. 1.53. **Effects of hinge-fold formation on the vitreous chamber.** If the diaphragm is above the imaginary hinge axis, it will be pressed downward as the hinge forms, and the vitreous pressure will rise



1.54

Fig. 1.54. **Reducing the dome height over the "hinge" by dividing the flap into segments.** Dividing a scleral flap into multiple subsegments shortens the distance between the wound ends for each segment. The dome heights over the subsegments are smaller than over the complete flap. *A* Hinge of entire flap, *B* axes of its subsegments



1.55

Fig. 1.55. **Reducing the dome height by converging the ends of the incision.** If the base of a scleral flap is made narrower than its free border, the hinge line is shortened as the dissection proceeds, and the depth of the fold is decreased

1.3.6 Margin of Deformation

Obviously the globe cannot be totally protected from the effects of deforming forces. Yet clinical experience shows that not every deformation does jeopardize the surgical goal. Some degree of deformation can be tolerated in each phase of the operation, and this degree, which can be defined and quantified, is called the *margin of deformation*. It determines the necessary precision of surgical manipulations.

The margin of deformation that is available in a given case depends on the *surgical goal*. If the *pressure chamber is intact* (e.g., if the globe has not been punctured or incised), the margin of deformation is determined by the pressure that the ocular wall can withstand. If the *chamber is open*, the margin of deformation equals the volume of material that may escape from the eye without compromising the surgical goal. If **any volume loss** is unacceptable, the margin of deformation is zero. If the **loss of aqueous** is acceptable, the margin of deformation equals the volume of the anterior chamber. If **removal of the lens** is also proposed, the margin of deformation is increased by the lens volume. Finally, if **vitreous loss** is also compatible with the surgical goal, the margin of deformation equals almost the entire volume of the globe (Fig. 1.56).

A *large* margin of deformation is an important safety factor and gives the surgeon great freedom in selecting a procedure. On the other hand, a *small* margin of deformation limits surgical options, for it excludes any procedure that would deform the globe to an unacceptable degree. Increasing the margin of deformation, then, is an important aspect of *safety strategy* in ophthalmic operations. There are two ways of increasing the margin of deformation for the **pressure chamber of the entire globe**: One is to increase the strength of the ocular wall by providing a more secure wound closure that will withstand a higher pressure. Another way is to lower the intraocular pressure so that a greater volume displacement would be needed to produce a critical rise in pressure. This can be accomplished by reducing the production of aqueous[39] or by reducing the volume of vitreous.[40]

If the **globe is opened** and it is necessary to preserve the integrity of the vitreous chamber, there is only one way to increase the margin of deformation: by *reducing the vitreous volume*. The reduction of aqueous secretion is of no value in this situation.

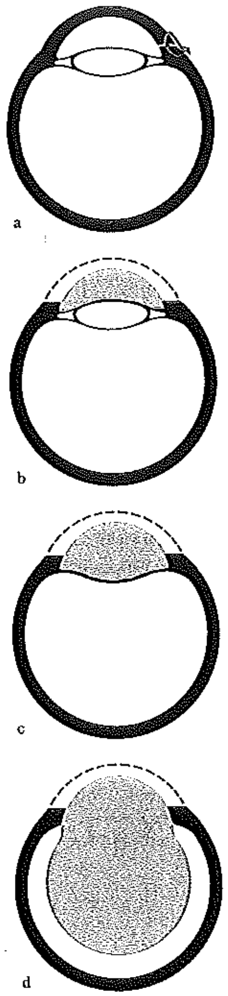


Fig. 1.56. Margin of deformation

a If the goal is to preserve the total intraocular volume, no loss of fluid or tissue is acceptable, and the margin of deformation is zero. The force that the globe can tolerate is determined by the pressure that the wound closure can withstand.

b If the goal is to preserve the vitreous chamber, aqueous loss is acceptable, so the margin of deformation equals the volume of the anterior chamber.

c If the goal is to preserve the vitreous chamber, and lens extraction is proposed, the margin of deformation is increased by the volume of the lens.

d If vitreous loss is acceptable, the margin of deformation equals practically the whole intraocular volume

One point cannot be overemphasized: *The margin of deformation is not a static quantity*. It changes continually during the course of an operation. All planned manipulations that have deforming vector components (see Fig. 1.45a) as well as all unplanned deformations consume a portion of the original safety margin. As a result, the tolerance to deformations may decrease as the operation proceeds.

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[39] Example: Carboanhydrase inhibitors.

[40] Example: Osmotically active substances, ocupression.

The surgeon, then, must closely monitor the available margin of deformation throughout the operation. It is the measure by which he must plan the procedure, and it tells him when he must switch to techniques that cause less deformation. A sudden decrease in the margin of deformation[41] is an important **warning sign**. If it is caused by the surgical measures themselves, the remedy is to change at once to techniques that have less deforming vector components.[42] If a sudden decrease in the margin of deformation cannot be ascribed to surgical manipulations, it must result from occult deforming forces that must be immediately identified and brought under control.[43]

1.3.7 Summary of Safety Strategy for External Forces

Deformations by external forces can be utilized to achieve specific goals, i.e., pressures can be raised to effect the *deliberate* expression of tissues (e.g., the lens or its nucleus). *Unintended* deformations, however, are a major source of complications, for they lead to inadvertent tissue expulsions (e.g., iris or vitreous prolapse). The goal of the safety strategy is to protect the intraocular compartments from the effects of unplanned forces.

The immediate goal of protective measures is to eliminate from the outset forces that cause unintended deformations of the ocular chambers (**prevention**). Therefore, the first step to safe surgery is the careful *preparation of the operative field* (see Chap. 3). During the operation, planned forces are applied in ways that cause minimal deformation, i.e. *positioning movements* are performed about the center of rotation of the globe (Fig. 1.44c), and *working movements* are applied tangentially (Fig. 1.45b). Deformation by hinge folds is prevented by employing techniques that do not require the elevation of flaps or, if a flap must be raised, the incision is tailored in a way that prevents excessive infolding or inversion of the ocular wall (see Fig. 1.51d, 1.54, 1.55).

Because total prevention is impossible, **defensive** measures are implemented to resist the deforming forces and protect the chambers from their effects. The ocular wall may be reinforced externally by attaching a *corset system* or internally by the introduction of *viscoelastic material*.

Because all these measures are of limited efficacy, every attempt is made to **increase the tolerance** of the chambers to deformations. A large **margin of deformation** is the most important safety factor that can be provided. Preoperative measures that reduce the pressure or volume of the vitreous establish the baseline margin of deformation. The *intraoperative* safety strategy is to stay within these established limits by avoiding any deformations that are not essential to accomplishing the surgical goal.

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[41] Evidenced, for example, by a rise of intraocular pressure or vitreous pressure (i.e., forward movement of the diaphragm, see Fig. 1.40b).

[42] E.g., instrumenting parallel to the ocular surface rather than perpendicular to it, avoiding techniques that cause expression.

[43] E.g., the contraction of extraocular muscles, choroidal hemorrhage ("expulsive hemorrhage").

2 Tissue Tactics

Whereas spatial tactics involve the application of pressure and resistance to control spatial volumes, tissue tactics are concerned with the application of forces to *displace, divide, and unite tissues.* For atraumatic tissue manipulations such as grasping, it is desirable for the forces to be applied over the largest area possible, as determined by anatomic constraints. For procedures that create lesions in tissues, such as sectioning, the forces should be applied over the smallest area possible.[1]

In practice it is rarely possible to apply forces in such a way that all the resultant vectors act exclusively in the desired direction. Besides these "intended vectors," surgical instruments always produce "unintended vectors" that displace or deform tissues. These side-effects can alter the direction of applied surgical forces in such a way that the result is inconsistent with the surgeon's intent.

The *effects and side-effects* of an **instrument** may be referred to as its *functional characteristics.* They determine the optimum mode of application of the instrument. In addition, every **tissue** has its own mechanical characteristics (*homogeneity, elasticity, cohesion,* etc.) which call for a specific mode of application of surgical instruments. The interaction of instrument characteristics and tissue characteristics forms the central theme of general tissue tactics. Analysis of this interaction discloses techniques for the optimum utilization of instruments in any given situation, or at least for the most satisfactory compromise if an optimum solution is not possible.

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[1] The critical parameter is pressure, which for a given force is inversely proportional to area.

2.1 The Application of Mechanical Energy

Mechanical forces are vector quantities which have magnitude and direction. The amount, or magnitude, of the force that can be transmitted to tissues is limited by the "**stability**" of the instrument used. If increasing force is applied to an instrument that is not sufficiently resistant to deformation (i.e., less resistant than the tissue), the force will deform the instrument rather than exert the intended effect on the tissue, and the instrument will deviate from the desired direction. To "transmit his will to the tissue," then, the surgeon should always select the most stable instrument that anatomic conditions will permit.[2]

As a general rule, forces that are not to interfere with each other should be applied independently. They may be applied at different times ("temporal separation"),[3] or, if several vectors are applied simultaneously, their mutual interference can be minimized by applying them at right angles to one another ("spatial separation"). The **rule of vector separation** should be incorporated into instrument designs so that the actual working motion of the instrument can be separated from subsidiary motions, and these in turn from the guiding motion through tissues (Fig. 2.1).

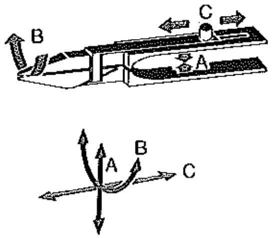

Fig. 2.1. **Rule of vector separation**, illustrated for a needleholder. The working vector *A* of the needleholder (grasping the needle) is perpendicular to the direction of needle guidance (*B*). Perpendicular to both is vector *C* (motion of the slide catch), arranged so that it will not interfere with instrument operation

2.1.1 Handles

The handle transmits forces from the fingers to the working end of the instrument, so it critically affects the precision with which the surgeon can "transmit his will to the tissue." Criteria for selecting the optimum handle for a given instrument are the type of feedback system and the spatial tactics that the surgeon wishes to employ.

With **tactile feedback**, the handle not only serves as a medium for transmitting manual forces (output) but also conveys information on tissue resistance back to the operator (input). The surgeon uses this information to regulate the forces he transmits to the tissue.

His assessment is based on an evaluation of the instrument position and the changes in that position. This process is aided by a handle design which yields unambiguous tactile and proprioceptive feedback when the instrument position is changed (Fig. 2.2).

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[2] This contradicts the common belief that fine instruments are superior to more heavy-duty instruments because of their smaller dimensions. In suturing, for example, a tissue-holding forceps that is too small will not offer sufficient resistance to the advancing needle and will bend; the tissue is deformed, causing the needle to deviate from the intended path.

[3] Examples: 1) Separate the working and guiding motions when cutting with scissors: Do not advance or swivel the scissors while closing the blades (cutting), do not close the blades while advancing. 2) Separate the guiding and control motions in intrascleral lamellar cutting or suturing: The control motion is the lifting of the instrument tip (needle or knife tip) buried within the scleral tissue so that its position can be visualized. Do not lift while cutting, and do not advance the cutting instrument while lifting.

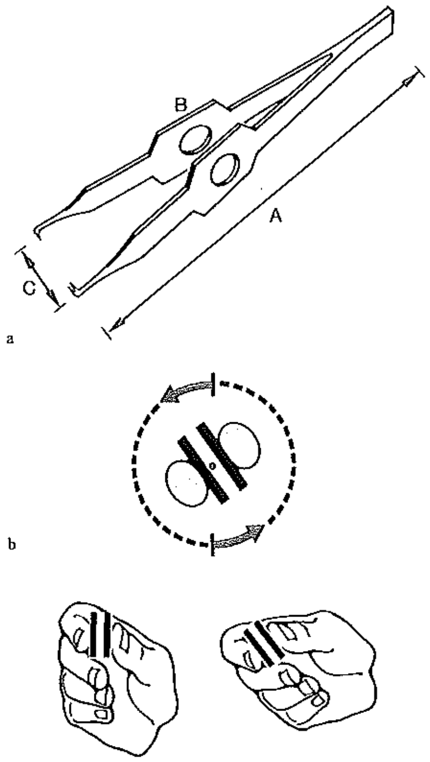

Fig. 2.2. **Stabilizing forceps handle**

a Tactile sensation is enhanced by placing minimal weight and tension on the fingertips.[4] This is accomplished by the following design features:
A Long handle: The weight of the instrument is borne by the metacarpus, leaving the fingertips free to guide the working end. The handle is supported at three points, making it easier to judge its position in space.
B Wide finger grips: Result in minimal finger pressure for a given force.
C Large blade opening: The increasing tension during closure of the spring handle is distributed over a long distance and therefore places minimal stress on the fingertips.

b Proprioceptive feedback is greater when motion at numerous joints is needed to redirect the handle. This is accomplished by the wide, flat grips, which require motion at the interphalangeal joints, metacarpophalangeal joints, and wrist (rotation and supination of the forearm). The schematic cross-section through the fingers and grips shows that rotation of the handle requires rotation of the fingers about the central axis of the instrument (red point)

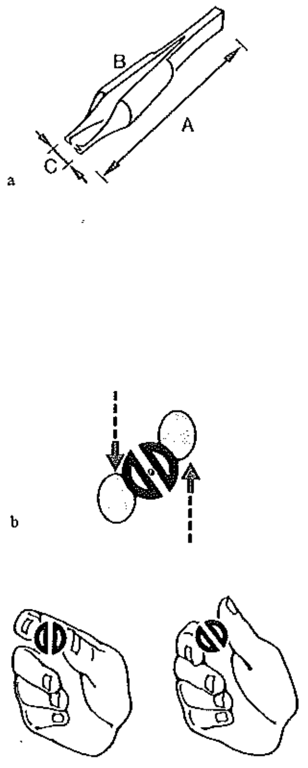

Fig. 2.3. **Versatile forceps handle**

a The short blade length (*A*) and narrow grips (*B*) provide increased mobility. The small blade opening (*C*) puts a greater load on the fingers but facilitates visual monitoring through the microscope.

b The finger grips are rounded so that the handle can be rotated about its axis with a slight motion of the fingertips. The wrist is not moved. The schematic diagram shows that simple motions of the fingers in opposite directions are sufficient to rotate the forceps

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[4] Sensitivity $= \delta J/J$ according to the Weber-Fechner law (J: Intensity of stimulus).

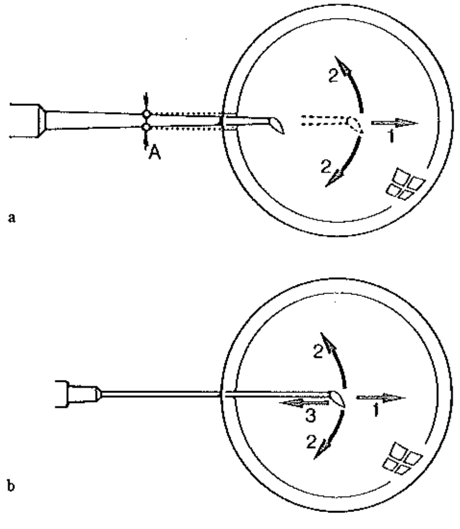

Fig. 2.4. **Handles for no-flow systems (illustrated here for a cystitome)**

a Conical handle: Water tightness improves as the knife is advanced, but withdrawal permits uncontrolled leak. Conical handles seal the wound only during insertion (*arrow 1*) and lateral swiveling movements (*arrow 2*). There is one dilemma associated with the use of conical handles: If the width of the handle just behind the blade equals that of the cutting edge (and therefore that of the incision), the instrument cannot be passed deeply into the chamber. But if the handle width equals the incision width at a site farther back on the handle (point *A* in the figure), wound leak can occur until the instrument has been inserted to that point. The problem of wound leak in this intermediate phase can be mitigated by advancing the cystitome very rapidly.

b Cylindrical handles seal the incision even as the instrument is withdrawn (*arrow 3*), provided the cross-section of the handle equals that of the blade. This places very high demands on the manufacture of the instrument, because the cross-section of the blade is difficult to define, and the handle must be custom-tooled to match it precisely

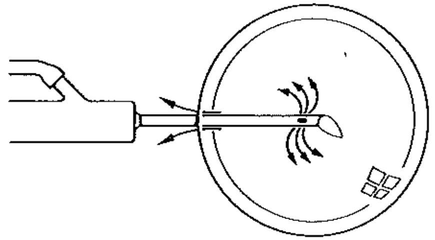

Fig. 2.5. **Infusion handle for controlled-flow systems.** The handle is hollow and serves as an infusion channel. Fine instruments have a narrow lumen. Therefore, the inflow resistance is high and a high inflow pressure is needed (pump, syringe)

Visual feedback does not rely on sensory input from the handle. Handles that can change their working direction with a minimum of motion and effort are suitable when visual feedback is employed. This design is advantageous in that the hand may rest on a support while only the fingers operate the handle. The small dimensions and short travel of the instrument facilitate monitoring in the small field of the operating microscope (Fig. 2.3).

Handles that require greater finger and wrist motion to change their position are suitable for stationary use such as fixation (Fig. 2.2). Handles that can be controlled with minimal finger motion are more versatile and facilitate guidance movements that involve direction changes.

When selecting the handle shape for a particular **space-tactical system**, it must be considered whether the handle needs to seal the access opening. A no-outflow system requires an extremely effective *seal*, and the system stands or falls with the design (and mode of guidance) of the handle. Handles with a *conical* stem produce an effective seal while they are advanced, but the slightest withdrawal will compromise the seal and allow aqueous leak (Fig. 2.4a). This problem does not exist with *cylindrical* handles, which may be freely advanced and withdrawn (Fig. 2.4b). In systems that incorporate fluid inflow (controlled-outflow systems and no-outflow systems with infusion), handles may be designed as *hollow tubes* to provide an access channel for the infusion (Fig. 2.5).

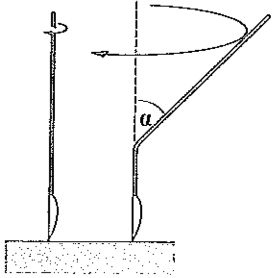

Fig. 2.6. **Guidance and working motions for simple handles.** *Left*: With a straight handle, rotation of the blade requires an identical rotation of the handle. *Right*: With an angulated handle, the blade is rotated by a swiveling motion of the handle whose amplitude depends on the angle α

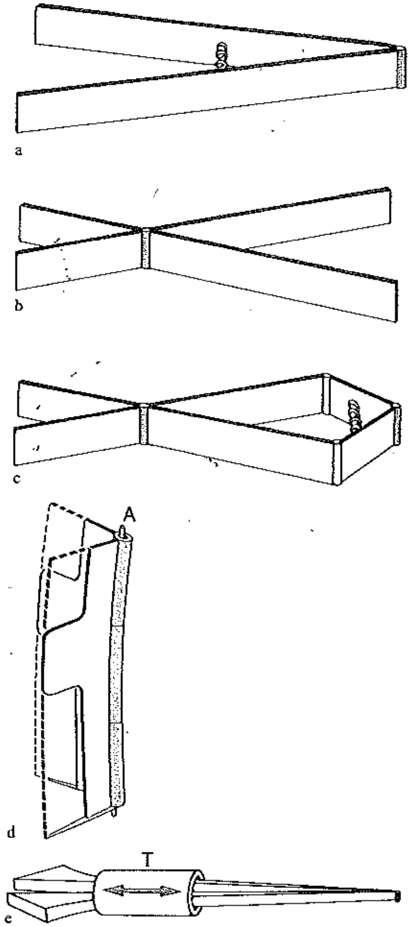

Fig. 2.7. **Force transmission and stabilization in two-piece handles**

a Simple forceps handle: The working part and handle are identical. Force transmitted from the fingers to the jaws is not mediated by a stabilizing joint. The precision of closure depends entirely on the stable and precise construction of the blades.

b Scissors handle: The joint (screw) is very short in relation to the blades, so precision depends largely on precise finger movements.

c Spring handle: An extra joint stabilizes blade closure and makes it more precise.

d Hinged handle: The joint length is maximal and equals that of the entire handle. The length of the force-transmitting lever arm does not depend on the total length of the handle. The spring tension necessary for opening is produced by a slight flexure of the joint (*A*).

e Tube handle: Very fine blades are enclosed in a stabilizing guide tube (*T*), which is slid forward to close the jaws

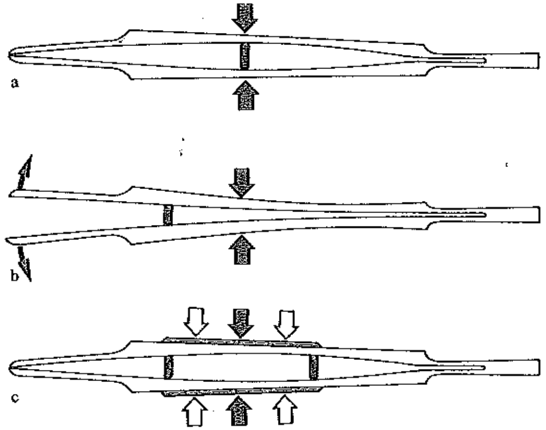

Fig. 2.8. **Regulation of force by stops.** Stops limit the pressure that can be applied to the instrument handle.

a To work properly, the stops must be placed directly below the point of finger contact.

b If the handle is squeezed behind the stops, the jaws will separate instead of close.

c When two stop pins are provided and the intervening handle is reinforced, finger pressure may be applied over a larger area

Another technical criterion for the design of handles is the relation of the working motion to guidance motions. In **one-piece handles** the working and guidance motions are performed in the same direction, the amplitude of the motion depending on the angle between the handle and the working end (Fig. 2.6). In **two-piece handles** the working and guidance motions act in different directions. While both parts of the instrument are guided in the same direction, the working motion consists of two countermovements about a connecting joint or axis. *Force transmission* from the handle to the working end (jaws) is a matter of leverage and depends on the relative lengths of the handle and jaws. The *precision* of the force transmission depends on the quality of the joint. Thus, the shorter the jaw length in relation to the handle, the higher the transmitted force and the greater the necessary stability of the joint (Fig. 2.7). If larger forces are applied to the instrument than its construction provides for, its components will bend, and the jaws will not appose correctly.[5] Precision instruments should therefore be fitted with *stops* which limit the force that can be applied (Fig. 2.8).

Besides considerations of force transmission, anatomic and geometric factors are relevant to selecting an appropriate instrument design. For operations in the interior of the eye, it is advantageous to use instruments whose working axis can be placed very close to the access opening. This will ensure a minimum instrument cross-section in the opening when tissues are cut or grasped, allowing the instrument to be used freely through an aperture of minimal size (Fig. 2.9).

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[5] This problem can be reduced by using a more rigid steel for the jaws than for the flexible spring handles. Precision instruments of this kind are recognized by the soldered joint between the handle and working end. (Note that the melting point of the solder limits the sterilization temperature).

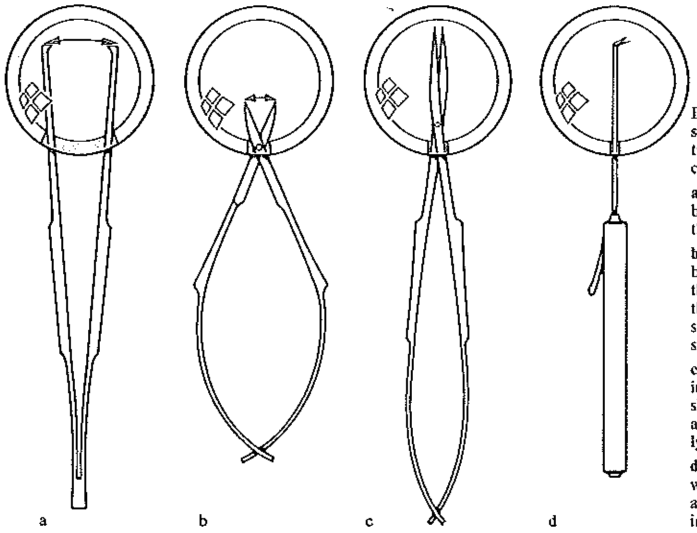

Fig. 2.9. **Geometric factors relating to the selection of blade length,** illustrated for two-piece instruments used in the anterior chamber.

a Simple forceps handle. The maximum blade opening is limited by the width of the chamber incision.

b In articulated handles, the blades may be opened without regard for the size of the incision if the joint is held exactly at the entrance. Spring-handled scissors with short blades may be used close to the incision.

c Scissors with long blades can work deep in the chamber. In the type of scissors shown here there is very little separation at the incision owing to the slender, slightly curved blades.

d Instruments with tubular handles always have a constant cross-section in the access opening, regardless of the depth of insertion

Motorized Handles

Handles in which the working motion is motor-driven convey no tactile impression of tissue resistance, so the surgeon must rely entirely on visual feedback. As there is no risk of interaction between the working and guidance motions, motorized handles are appropriate for high-precision work in which the surgeon must concentrate entirely on guiding the instrument.

Rotating knives (trephines, circular knives) have "infinite" blade excursions which offer the advantage of consistent cutting quality owing to their long, uniform cutting action. The main risk is that the rotating blade will snag unsectioned tissue fibers and cause the tearing of tissues remote from the intended site of action.

This danger is avoided by the short excursions of **oscillating knives**. The amplitude of the blade motion is limited by the design, making it safe to operate the instrument at extremely high speeds. It must be considered, however, that individual blade movements are invisible at high speeds (Fig. 2.10), so the cutting process cannot be *monitored* by watching the blade itself but only by observing its effect on the tissue.

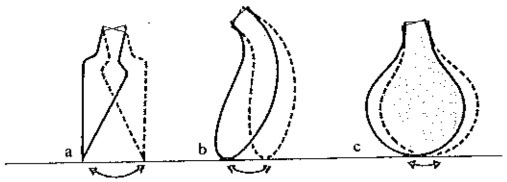

Fig. 2.10. **Oscillating blades**. Individual blade movements are invisible at high frequencies, and only the overlapping portion can be seen (*gray*). Note that the tip of the blade in contact with the tissue is invisible in a and b but can be seen in c

2.1.2 Grasping

Grasping serves to transmit guidance motions to a substrate. The *guidance motion* may be an active movement performed to **mobilize** the substrate (e.g., for transposition or removal), or it may be a stationary action intended to **immobilize** the substrate (e.g., for tissue fixation during cutting or suturing).[6] In order for force transmission to occur, a frictional resistance must be created between the instrument and substrate. The necessary level of this resistance depends on the forces that must be overcome by the guidance motion.

Frictional resistance is determined by:
- the *forces* exerted on the substrate;
- the *area of blade contact*;
- the *angle* at which the forces act on the substrate.

To preserve structures during the grasping of *tissues*, high pressure should be avoided whenever possible and the necessary friction produced by increasing the area of blade contact or selecting a more favorable angle of attack. When grasping a *solid object* such as a needle, however, the grasping area is limited and the angle of attack is predetermined, so friction is produced mainly by applying a large gripping force.

Spatulas

Solid Spatulas

With a solid spatula, force is transmitted directly from the handle to the area of tissue contact. This ensures a high precision in grasping.

Simple spatulas are suitable for forward and lateral pivoting movements (Fig. 2.11). **Hooks** are used for snaring and pulling tissues. *Blunt hooks* can be moved freely in all directions without traumatizing adjacent tissues but can be used only to grasp and apply traction to free edges (e.g., the pupillary border or implant margins) (Fig. 2.12). *Sharp hooks* can also engage tissue surfaces but may traumatize surrounding tissues. Hence a special technique is required for inserting and removing sharp hooks through incisions (Fig. 2.13).

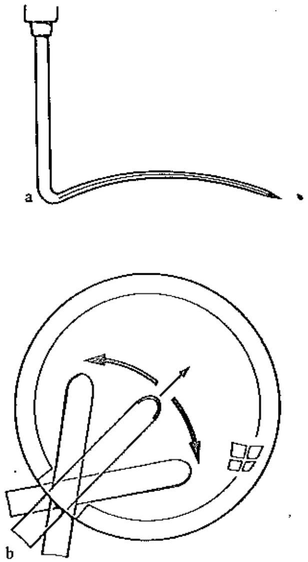

Fig. 2.11. **Simple spatula**

a The simple spatula has a uniform cross-section over its entire length, so it can be guided in a way that keeps the incision watertight during all manipulations (see Fig. 5.18D for suitable type of incision). Long blades are slightly curved to conform to the curved intraocular surfaces.

b The basic working motions of the simple spatula are thrusting (small working surface, high pressure), pivoting (larger working surface, lower pressure), elevation and depression (largest surface). The lateral working surfaces are shown in *red*

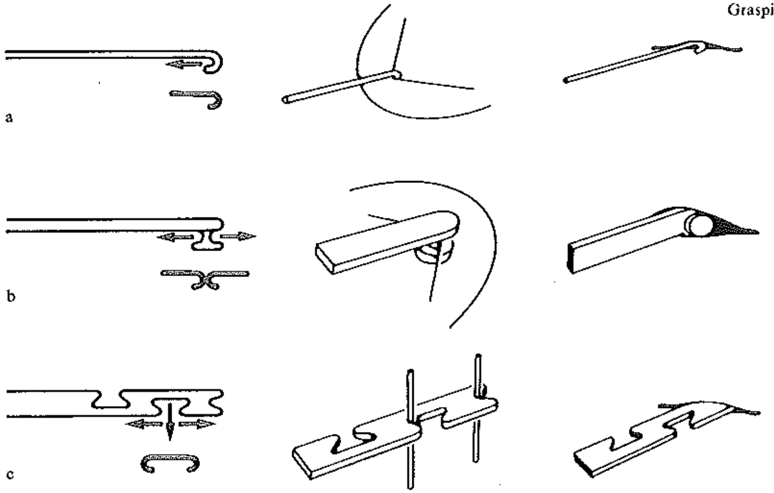

Fig. 2.12. **Blunt hooks**. *Left*: Design principle. *Center*: Possible applications in tissue. *Right*: Introduction through incisions.

a Simple hook for applying traction to tissue. The hook is turned sideways for insertion through an incision.

b Collar-button probe: Consists basically of an infinite number of blunt hooks in a centrifugal arrangement, can push or pull in any direction. The probe is inserted sideways so it will not catch the wound edge.

c Flat spatula with notches: Consists basically of several hooks pointing in opposite directions, can pull or push strands and posts in any direction; slips smoothly through small incisions

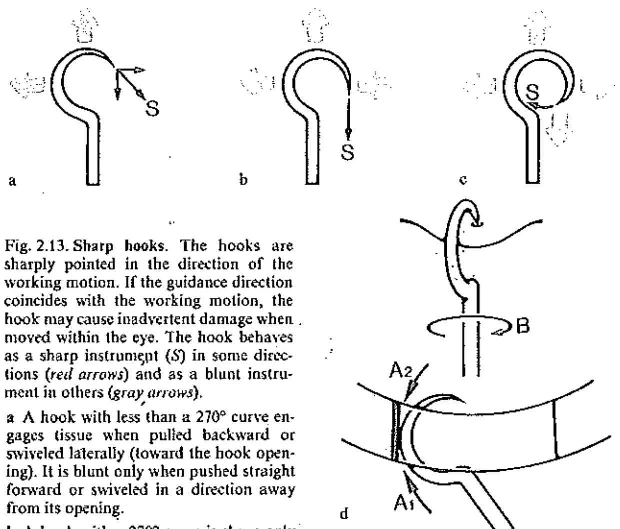

Fig. 2.13. **Sharp hooks**. The hooks are sharply pointed in the direction of the working motion. If the guidance direction coincides with the working motion, the hook may cause inadvertent damage when moved within the eye. The hook behaves as a sharp instrument (*S*) in some directions (*red arrows*) and as a blunt instrument in others (*gray arrows*).

a A hook with less than a 270° curve engages tissue when pulled backward or swiveled laterally (toward the hook opening). It is blunt only when pushed straight forward or swiveled in a direction away from its opening.

b A hook with a 270° curve is sharp only when pulled straight backward. It is blunt in all other directions.

c A hook with more than a 270° curve can be safely maneuvered in all directions. It is sharp only when rotated to engage tissue prominences (e.g., iris trabeculae).

d For passage into or out of an incision, a sharp hook is turned sideways with its back surface pressed against one side of the wound (*A*). Having traversed the incision, the hook is rotated into the working position (*B*)

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[6] Versatile handles are preferred for active manipulations, stable handles for fixation (see Fig. 2.2).

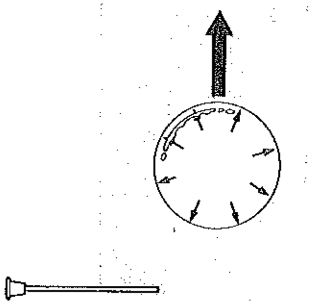


Fig. 2.14. **Bullous spatula.** A bubble exerts force as an instrument without manipulation by the operator. It exerts centrifugal forces on the environment by virtue of the surface tension and internal pressure that give the bubble its spherical shape. In addition, gravitational effects produce upward-directed forces in light bubbles and downward-directed forces in heavy bubbles

Bubbles as "Spatulas"

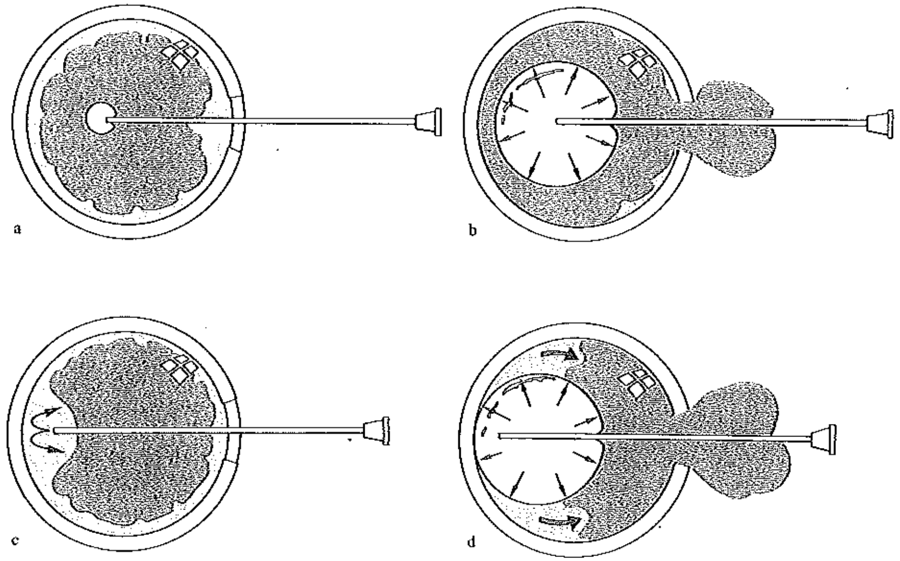
Bullous "spatulas" can transmit forces to tissue in two ways: their surface tension can exert *centrifugal* forces, and their buoyancy can exert *vertical* forces (Fig. 2.14). These forces can be used to impose a spherical shape on surrounding tissues or to force tissues upward or downward.

Bullous spatulas can be introduced through openings of minimal size but, once in the chamber, can attain a considerable volume. This discrepancy can be utilized to apply forces over a broad area (Fig. 2.15).

The forces are independent of the actions of the surgeon, who can directly control only the *size* of the "spatula" and indirectly controls its *position*. But this very independence can be utilized to maintain the effect of the spatula after its placement and to change its site of action.

The positional dependence of the effect compels the patient to maintain a certain position for as long as the bubble is in the eye. This requirement can be moderated somewhat by embedding the bubble in a highly viscous material to restrict its mobility (Fig. 2.16).

The injection technique is the same as described earlier in connection with spatial tactics (see Figs. 1.33–1.35).



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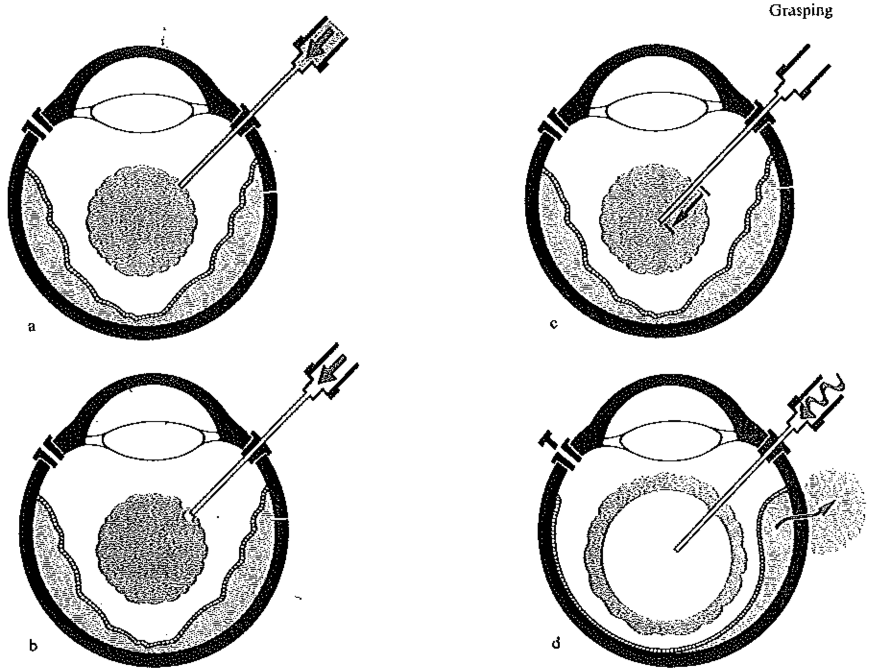

2.16

Fig. 2.15. Air bubble as a mobilizing instrument (for expelling viscoelastic material from the anterior chamber)

a, b Unsuccessful attempt using improper technique. **c, d** Correct technique.

a Air injected directly into the viscoelastic material produces a viscoelastic balloon.

b If one then attempts to remove the material by enlarging the bubble, only a portion is expelled; the rest is pressed against the opposite chamber angle.

c The expulsion is first prepared by creating a watery (homogeneous) compartment. Watery fluid is injected behind the viscous material to create a nonviscous space on the opposite side.

d Expulsion is then accomplished by injecting air into the watery compartment. The air bubble forces the viscoelastic material out of the chamber.

Note: Control of the expulsion is aided by maintaining a low outflow resistance for the viscoelastic material (by opening the wound edges as in Fig. 2.24). If the resistance is too high, the chamber pressure will rise, and side-effects may occur. This pressure rise can be detected by noting that enlargement of the bubble is insufficient relative to the volume of air injected

Fig. 2.16. "Spherical spatula": viscoelastic balloon produced by injecting gas into a viscoelastic mass (here: To reduce and stabilize a detached retina)

a Preparation of the viscoelastic shell: Viscoelastic material is injected into the vitrectomized cavity.

b Unsuccessful attempt to inflate the balloon: If the cannula is not repositioned after injecting the viscoelastic material, and gas is injected simply by exchanging syringes, gas bubbles will form at the interface between the viscous substance and watery fluid. In this nonhomogeneous milieu the gas bubbles will follow the path of least resistance and escape into the watery milieu.

c Correct technique for inflating the balloon: Before gas is injected, the cannula is advanced into a homogeneous milieu by positioning its tip at the center of the viscoelastic mass.

d The cannula having been repositioned, the viscoelastic mass is now inflated to produce an absorbable intraocular balloon

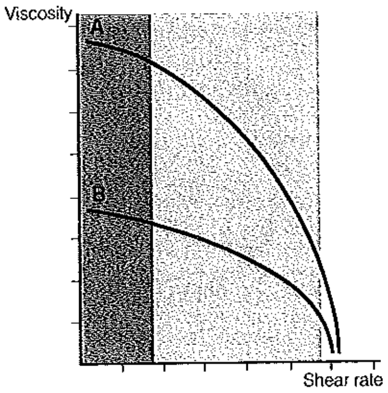

Fig. 2.17. Suitability of various viscoelastic materials for use as a spatula, i.e., for viscostabilization and viscomobilization. The maximum viscosity of the material (i.e., the initial viscosity at a low shear rate) determines its stabilizing effect and thus its efficacy as a "permanent spatula" (*dark gray* zone) The medium viscosity (viscosity at a medium shear rate) determines the suitability of the material for mobilization and thus its efficacy as a "soft spatula" (*medium gray*). The minimum viscosity (viscosity at a high shear rate) determines injectability through thin cannulas (*light gray*). The high-molecular substance *A* makes a more effective spatula than the low-molecular substance *B*. Both have comparable injectability (see Fig. 1.18)

Viscoelastic Materials as Spatulas

Viscoelastic spatulas, like bullous spatulas, can apply forces atraumatically over a large area even when introduced through small openings. But they differ from bullous spatulas in that their effect is not position-dependent (provided the specific gravity of the viscoelastic substance equals that of the aqueous).[7] They differ from solid spatulas in that the link between surgeon and tissue is influenced by the viscosity of the material; control is indirect and consequently less precise.

Viscoelastic materials may be characterized as **"soft permanent spatulas."** As they are injected, they displace tissues and act as *soft* spatulas to produce a nontraumatizing *visco-mobilization*. After the injection they function as *permanent* spatulas by holding the tissues in place and providing a long-term *immobilization* ("visco-stabilization").

Their high internal flow resistance and elasticity enable viscoelastic spatulas to transmit forces to their surroundings (Fig. 2.17). The *effect* depends on the ratio of the internal resistance of the spatula to external resistances. This ratio determines whether the viscoelastic spatula, when introduced, will displace the surrounding tissue or will be displaced by it (Fig. 2.18).

The viscoelastic material may block its own flow by damming back toward the cannula, causing subsequently injected material to spread along paths of least resistance. Thus, the surgeon cannot predict the effect of the viscoelastic spatula based on the position of the cannula or the force of the injection. As a general rule, however, the best effect is obtained when there is minimal distance between the cannula opening and the target site, for this reduces the area in which there may be unintended blockage or deviation of the flow.

Besides injecting close to the target site, **control is effected by modifying flow resistances** about the target site, the goal being to maintain a lower resistance in the intended flow direction than in all other directions. This principle is illustrated in Figs. 2.19–2.22. It will be noted

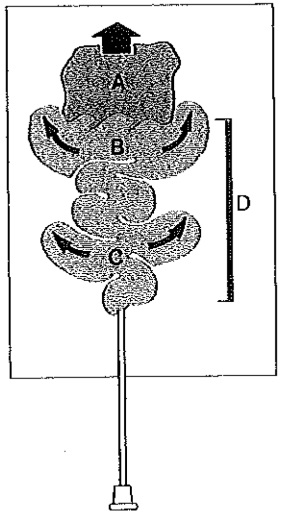

Fig. 2.18. Viscoelastic spatula. The relationship between the external resistance to displacement (friction and inertia) and the internal resistance of the material (viscosity) determines whether the viscoelastic material will displace the particle (*A*) or flow around it (*B*). For a given viscosity, the distance (*D*) between the cannula outlet and the target will determine whether the material evades (*C*) or acts on the particle

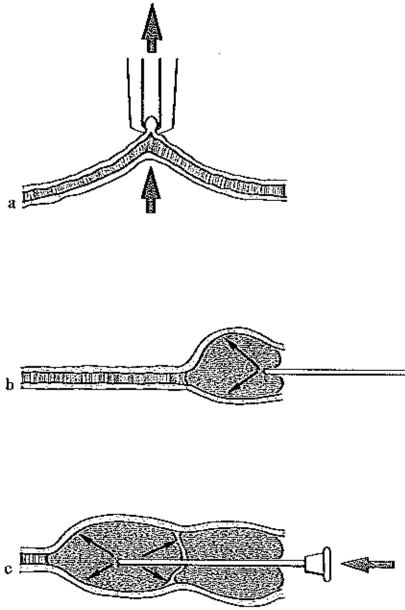

Fig. 2.19. Separation of adherent tissue layers with a viscoelastic spatula. Technique for cases where the resistance to separation of the layers is less than the reflux resistance of the viscoelastic material.

a Indication: Separation of thin, delicate layers that are too mobile and compliant to be pulled apart with grasping instruments.[8]

b The intermediate layer is located with the cannula tip, and the viscoelastic material is injected into the interspace.

c Because the reflux resistance is greater than the resistance to separation, the injected material is forced into the interspace and bluntly separates the layers.

Note: The cannula tip is pushed forward as injection proceeds to keep the distance between outlet and working area short (i.e. to minimize the distance D in Fig. 2.18)

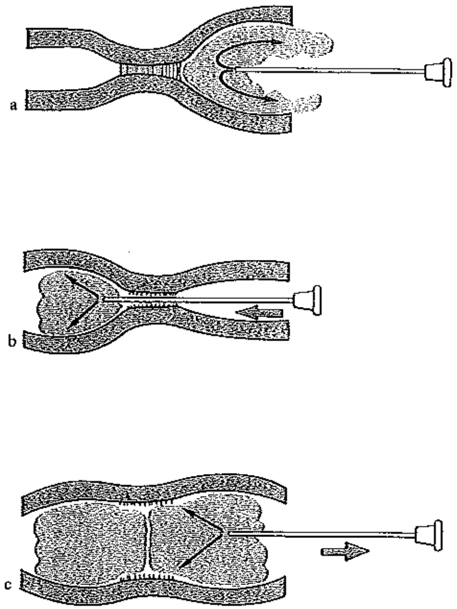

Fig. 2.20. Separation of adherent tissue layers with a viscoelastic spatula. Technique for cases where the resistance to separation of the layers is greater than the reflux resistance of viscoelastic material.

a Indication: Separation of firm adhesions between tough tissue layers.[9] Because the reflux resistance is lower, the flow of viscoelastic material is deflected away from the adhesion.

b It is necessary first to sever the adhesions with the tip of the cannula ("solid spatula") before injecting the material.

c The injection is continued while the cannula is withdrawn. Here the viscoelastic spatula does not effect the separation but functions as a permanent spatula to maintain the dehiscence created with the solid instrument

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[7] The viscoelastic spatula cannot exert its effect as long as a bubble can. Although the bubble will diminish in size with absorption, it retains its essential properties (i.e., it remains impermeable and continues to displace in accordance with its specific gravity). It will exert its effect as long as it retains a sufficient size. In the viscoelastic spatula, on the other hand, dilution of the material in the eye alters its viscosity and elasticity, and its effect diminishes even if it continues to occupy a sufficiently large volume.

[8] Examples: Separation of coagulated blood from the anterior surface of the iris; separation of a preretinal membrane from a detached retina.

[9] Examples: Separation of the ciliary body from the scleral spur (cyclodialysis, see Fig. 6.1); clearing of firm synechiae (see Fig. 7.30).

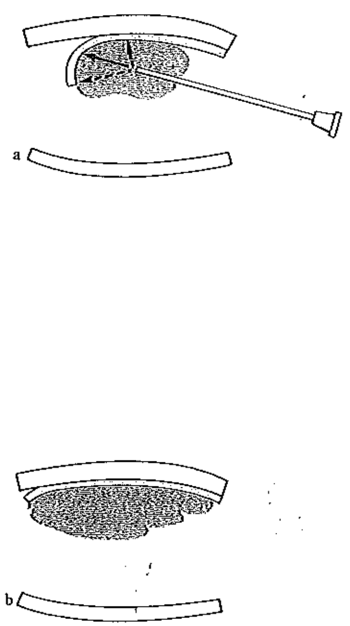

Fig. 2.21. Approximation of two separate tissue layers with a viscoelastic spatula. Technique for cases where the resistance to approximation of the layers is less than the reflux resistance.

a A fine membrane is approximated to another tissue layer.[10] The injection is directed obliquely to produce vector components perpendicular to the tissue surface (to effect the approximation) and also parallel to it (to advance the approximation). The viscoelastic material functions here as a soft spatula.

b The injected material keeps the membrane approximated to the substrate, functioning now as a permanent spatula

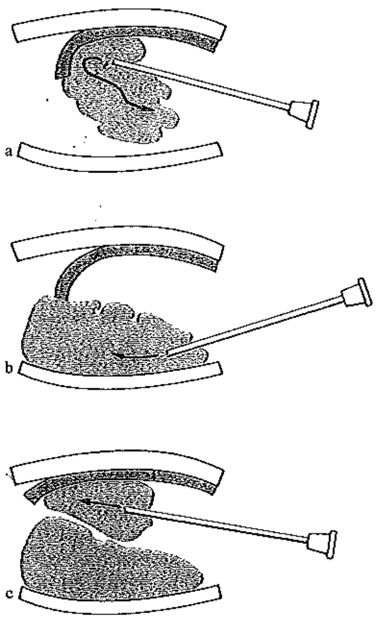

Fig. 2.22. Approximation of two separate tissue layers with a viscoelastic spatula. Technique for cases where the resistance to approximation is greater than the reflux resistance.

a When an attempt is made to press the firm tissue layer against a substrate, the flow of material is deflected onto a path of lesser resistance, and reflux occurs.

b The initial step, therefore, is to block that path with viscoelastic material.

c In a second step the "soft spatula" is injected to approximate the tissue layers (analogous to Fig. 2.21a)

that the viscoelastic material itself can provide resistance to flow in undesired directions.[11] This effect can be enhanced by the use of higher-viscosity materials (substance A in Fig. 2.17).

If material with sufficiently high viscosity is not available, resistance may be decreased in the desired direction by using a solid instrument (e.g., the cannula itself) to clear any obstructions along the intended path of flow. The viscoelastic material is then injected and will function as a permanent spatula to maintain the dehiscence (Fig. 2.20).

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[10] Examples: Replacement of a detached Descemet membrane; reapposition of a torn lens capsule to the hyaloid membrane (see Fig. 8.108).

[11] Gas bubbles may be used to increase resistance *above* the target site (see Fig. 7.35b).

The Use of Watery Fluids for Mobilization and Grasping

Watery fluids can exert forces through pressure gradients, and their control consists accordingly in the regulation of pressures and resistances. The operator may employ positive pressure as a means of mobilizing tissues (irrigation) or negative pressure as a means of grasping tissues (aspiration).

Irrigation

Irrigation can be used both to mobilize tissues and to transport them. In **irrigation for mobilization**, the irrigating stream dislodges tissue particles from surfaces to which they are adherent. Hence the fluid stream must produce *force vectors directed away from the tissue surfaces*. Such vectors are produced by the negative pressure that arises at sites of narrowing as a result of asymmetric flow. The magnitude of this effect, called *dynamic lift*,[12] depends on the flow velocity around the particle to be mobilized (Fig. 2.23C). Irrigation for mobilization, then, must employ a high-velocity fluid stream. The flow velocity is highest at the cannula outlet (Fig. 2.23A), so the cannula tip is placed as close as possible to the particle to be mobilized.[13] The optimum flow direction is not squarely onto the particle, but parallel to the surface to which the particle is adherent.

Irrigation for transport of tissue material suspended in the stream is actually a simple fluid exchange analogous to *space-tactical fluid systems*.[14] Thus, the tip of the cannula may remain close to the access opening. Low velocities are sufficient and also optimal because they are easier to control. This procedure differs from space-tactical systems in that the *flow resistances* in irrigation are not geared toward considerations of pressure but toward the size of the particles to be transported. In practical terms this means that flow paths must be kept wide enough to eliminate friction between the particles and tissue surface. The *control* of transport irrigation, then, involves regulating the outflow resistance in such a way that this *resistance remains high while the particle is being transported* through the chamber in order to keep the chamber volume large. However, *when the particle comes to trasverse the incision*, a *low outflow resistance* is needed since the outflow path from the chamber must be as wide as possible (Fig. 2.24).[15] Transport irrigation, then, employs a low-velocity fluid stream and a well-coordinated sequence of increased and reduced outflow resistances.

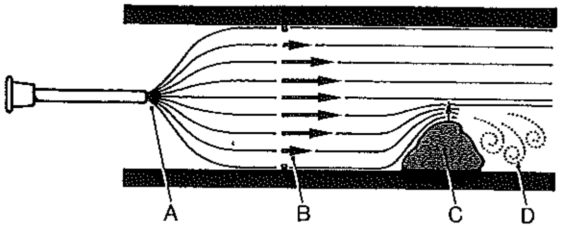

Fig. 2.23. Basic hydrodynamics of irrigation. At sites of narrowing in the flow channel, as over a particle, the flow velocity increases (i.e., the streamlines move closer together).

A The channel is narrowest in the irrigation cannula, so the flow velocity is maximal at the cannula outlet (see Fig. 1.15a).

B Velocity distribution in laminar flow: The flow velocity is always zero at the surface of solid bodies. The velocity increases with distance from the surface (*arrows*).

C Vectors perpendicular to the surface occur when the channel is narrowed by an obstacle. As flow velocity increases, pressure falls (Bernoulli's law), causing a lifting force to be exerted on a particle in the flow. The magnitude of this lifting force depends on the square of the flow velocity.

D Eddy currents can form behind the obstacle. The intensity of these currents depends basically on the shape of the obstacle and the flow velocity but cannot be predicted in a given case

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[12] Dynamic lift is the net upward force produced by asymmetric flow velocities around an object (such as an aircraft wing).

[13] This contrasts with fluid applications in spatial tactics, where the cannula tip is placed at the access opening.

[14] In fluid exchange, the particle and fluid have the same velocities, whereas in mobilization the fluid velocity is greater.

[15] This makes it necessary to provide an inflow capacity commensurate with the size of the particles to be transported.

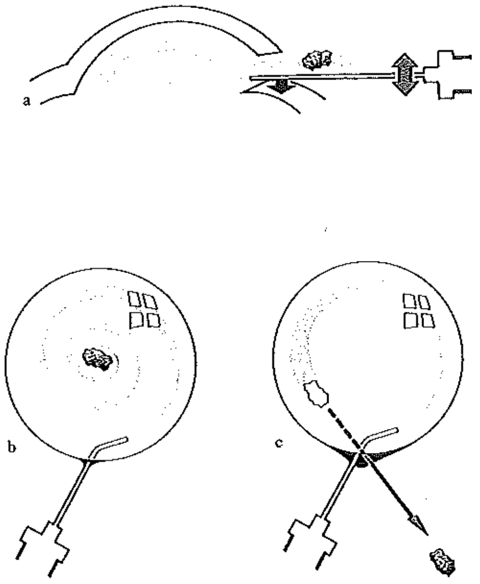

Fig. 2.24. Control of irrigation for transport: removal of material from the anterior chamber

a Inflow pressure is controlled by the pressure on the syringe plunger, outflow resistance by the degree of wound opening, i.e., by raising or lowering the cannula (see also Fig. 1.14).

b Mobilization of the particle inside the chamber: With a high outflow resistance, the anterior chamber will remain deep, and the irrigating stream will mobilize the particle and keep it flowing within the chamber. If the injection rate is too high, it will produce eddy currents instead of a uniform stream.

c Removal of the particle from the chamber: When the outflow resistance is lowered, the fluid stream and entrained particle will exit the chamber. The incision is not opened at the moment the particle is adjacent to it but somewhat earlier, when the motion vector of the particle (the tangent to its circular path of motion) is directed toward the incision

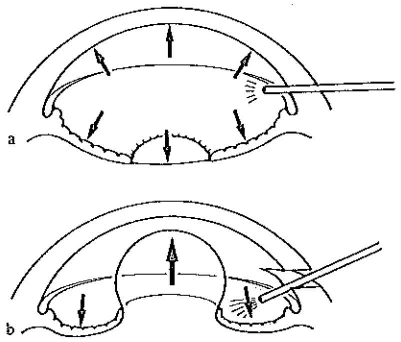

Fig. 2.25. Control of irrigation: Spatial tactics

a If the outflow resistance during irrigation is high, rising pressure in the anterior chamber can push the diaphragm inward and expand the chamber volume.

b If the outflow resistance is low, the chamber pressure does not rise as fluid is injected. The chamber contents are redistributed, but the chamber volume does not increase. If a portion of the diaphragm (iris) is pressed backward, another portion (anterior hyaloid) is extruded forward. If this occurs while the cannula tip is at the center of the chamber (and not at the access opening), the protruding part (e.g. vitreous) is at risk for injury

Aspiration

Aspiration allows for a more selective manipulation than irrigation. The *site* of the critical pressure gradient is strictly localized to the cannula opening, which is positioned precisely where the action of the pressure gradient is required. The magnitude of the pressure difference is influenced by the resistance at the cannula inlet. This resistance provides the distinction between aspiration by occlusion and aspiration by flow.

Aspiration by occlusion is a *mobilizing procedure*. The inlet of the cannula is completely occluded by the material to be mobilized, raising the *resistance* to infinity and causing a cessation of flow. The pressure gradient at the cannula tip is maximal and approaches the difference between the chamber pressure and the terminal pressure (Fig. 2.26a).[16]

Aspiration by occlusion is controlled by regulating both of these pressures. The *adhesion* of the particle to the cannula can be *increased*, and the particle "gripped" more tightly, either by increasing the chamber pressure (e.g., raising the infusion pressure) or by lowering the terminal pressure (i.e., increasing the suction).[17]

To *decrease the adhesion* of the particle to the cannula for the purpose of release, the opposite procedure is followed: either the terminal pressure is increased above the level of the chamber pressure, or the chamber pressure is reduced below the terminal pressure (by lowering the infusion pressure).

Once occlusion has occurred, fluid can no longer flow through the cannula, and there is no need for volume replacement by infusion.[18] Occlusion of the cannula also eliminates the danger of inadvertent tissue aspiration.

The *safety strategy* for aspiration by occlusion requires the suction to remain turned off while the tip of the cannula is placed against the particle to be grasped. Once it is certain that the particle occludes the cannula, the suction may be turned on. Note: Partial occlusion is no occlusion, and any aspirating maneuver will become aspiration in flow.

Aspiration in Flow. Aspiration in flow is a *transport procedure*. The inlet of the cannula is open, the *resistance low*, and the pressure difference correspondingly small (Fig. 2.26b). Flow through the cannula is continuous, and fluid infusion is mandatory for volume replacement. Aspiration in flow, like transport irrigation, is basically a *space-tactical fluid system* with the difference that the suction tip is placed selectively at a particular target.

Because the inlet of the cannula is open, anything in front of the opening will be aspirated. This increases the potential for inadvertent aspiration. This danger increases with the flow velocity, since eddy currents and dynamic lift can draw tissues from apparently safe regions into the area of the suction tip. The safety strategy for aspiration in flow requires low flow velocities, therefore.

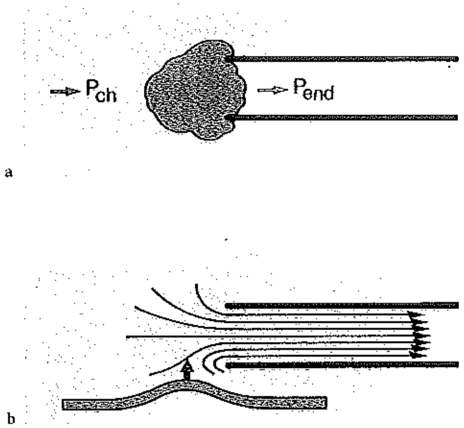

Fig. 2.26. Methods of aspiration

a Aspiration by occlusion: With total blockage of the aspirating channel, the resistance at the cannula inlet becomes infinitely high. The pressure difference at the inlet (P_{ch} vs. P_{end}) is maximal.

b Aspiration in flow: The cannula inlet is unobstructed, and the resistance is finite. The pressure difference at the inlet is the difference between the chamber pressure P_{ch} and the exit pressure P_{exit} and therefore is very small (see Fig. 1.2). At high flow rates, dynamic lift can occur at sites with asymmetric flow, drawing movable objects (here: a membrane) toward the inlet. This can occur even when the cannula is parallel to the surface of the object

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[16] Note: The level of the chamber pressure depends on how effectively the access opening is sealed around the cannula. If the outflow resistance next to the cannula is infinitely high (see Fig. 1.4a), the chamber pressure will equal the initial pressure. If the outflow resistance is zero, the chamber pressure will equal atmospheric (see Fig. 1.6).

[17] For example, if the chamber pressure is zero (due to a low outflow resistance to the external atmosphere, see Fig. 1.6), a strong suction is required. Conversely, if the terminal pressure is zero (e.g., in a cannula that communicates with the open air), a high infusion pressure is required.

[18] Compensatory fluid infusion is necessary only if there are other outflow sites besides the occluded cannula (see Fig. 1.5c).

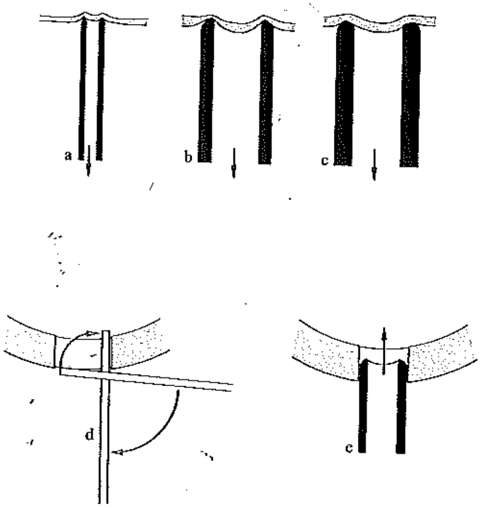

Fig. 2.27. Configurations of cannula openings. *Top*: Cannula tips in cross-section. *Bottom*: Guidance maneuvers for passing cannulas through incisions. All the cannulas can be used for irrigation, but only cannula **c** is suitable for aspiration by occlusion.

a Thin cannula: Thin cannulas also have thin walls, which act as a sharp instrument when pressed against tissue. This may occur during aspiration or during forward-directed guidance motions.

b Thick-walled cannula with a rounded outer edge: The cannula acts as a blunt instrument during guidance motions, but its inner edge behaves as a sharp instrument during aspiration.

c Thick-walled cannula with rounded inner and outer edges: The cannula acts as a blunt instrument even during aspiration.

d If the cannula has a sharp outer edge (e.g., cannula **a**), it should be passed side-first through incisions, as illustrated. This swiveling maneuver requires a relatively broad wound opening.

e Cannulas with a rounded outer edge (**b** and **c**) may be introduced point-first, so they can negotiate even narrow wounds

Cannulas for the Application of "Fluid Instruments"

The *shape of the tip* of the cannula is critical when the instrument is used for tissue tactics (unlike cannulas for volume maintenance, where only the cross-section is significant; see Fig. 1.12). The tip design is less critical for **irrigating cannulas** since all tissues are forced away from the opening. But in **aspirating cannulas**, which draw tissues toward the opening, even the slightest irregularity at the tip can increase the risk of inadvertent tissue lesions.[19] The tip design is especially critical in aspiration by occlusion (Fig. 2.27), where the integrity of the system depends on the *shape* of the rim (Fig. 2.29a). The *direction* of the opening determines the angle of application to the tissue and influences how the particle will reorient itself when occlusion is established (Fig. 2.28). If the material is to be transported through the lumen of the cannula, it is advantageous to have a lumen of larger caliber than the aspirating port (Fig. 2.29b).

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[19] This is of lesser importance for tissues that are deliberately aspirated (e.g., lens cortex, vitreous), but there is always a risk of aspirating tissues that should remain in the eye and whose damage could compromise the surgical goal (e.g., lens capsule, retina).

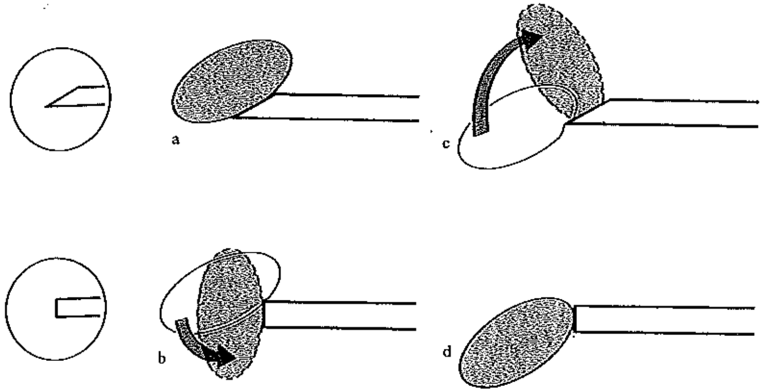

Fig. 2.28. Effect of cannula bevel on grasping
a, c Oblique bevel (opening faces laterally).
b, d Flat bevel (opening faces forward).
In **a** and **d** the cannula tip apposes flush to the tissue surface; in **b** and **c** it does not.

a An aspirating cannula whose oblique bevel matches the orientation angle of the particle surface (so the surfaces of the particle and cannula opening are parallel) can grasp the particle without changing its position.

b A flat-beveled cannula applied at the same site does not appose flush to the particle, so the latter must rotate into an orientation where the surfaces are parallel. This may be associated with unintended tissue contacts about the particle.

c An obliquely beveled cannula produces a similar rotation when applied to a vertical surface.

d The particle in **c** would not rotate if grasped at the same site with a flat-beveled cannula

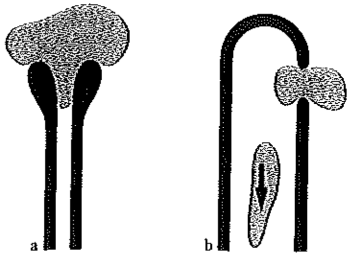

Fig. 2.29. Relationship of cannula opening and lumen in the grasping or aspiration of tissue

a Cannula for grasping only: The inner surface of the opening has a conical shape so that particles of various sizes can occlude the inlet, but its narrow lumen prevents the material from being aspirated through the cannula.

b Cannula for both grasping and transport: Here the lumen is larger than the opening so that particles encounter little resistance after passing through the inlet

Forceps

Nontoothed Forceps

Forceps without teeth must have a sufficiently large grasping surface in order to produce sufficient friction. Because they place relatively little pressure on the substrate, they can grasp and hold delicate tissues and materials without damaging them.

In forceps with a **variable grasping surface** (Fig. 2.30), the *flexibility* of the blades determines whether increased pressure with the fingers will enlarge the contact area or raise the grasping pressure. If the blades are very rigid, the pressure increases considerably before the grasping surface can enlarge sufficiently, and the tissue is crushed. But if the blades are flexible, the pressure remains low, and little friction develops despite the large grasping surface.[20]

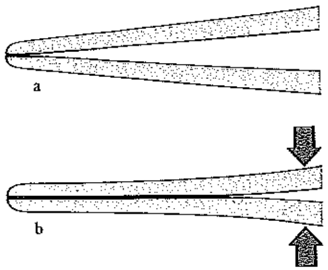

Fig. 2.30. **Plane forceps with undefined grasping surface.** As increasing force is applied to the blades, the grasping area increases (**b**), but the jaw pressure (=force per unit area) does not rise accordingly. Thus, the efficacy of the instrument relies on the contact area (and friction) that is established between the blades and the object grasped

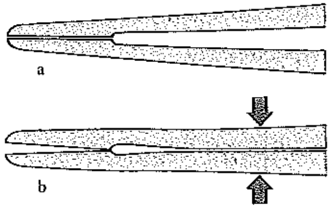

Fig. 2.31. **Plane forceps with predefined grasping surface**

a The grasping surfaces meet only when a specific blade pressure is applied.

b If greater pressure is applied, the grasping surfaces begin to separate and, in contrast to Fig. 2.30b, the effective grasping area is diminished

In forceps with a **predefined grasping surface** (Fig. 2.31), the blade pressure is determined by the construction. If the pressure on the blades is too low, only the tips will meet; if too high, the jaws will separate. *Pressure-regulating devices* are necessary, therefore (see Fig. 2.8).[21]

Serration on the inside of the jaws increases the grasping surface of the forceps and changes its angle of attack on the tissue. This provides increased friction without altering the dimensions of the forceps (Fig. 2.32).

However, serration is effective only in soft material whose surface can conform to the shape of the ridges. Serration produces the opposite effect in hard material, because it reduces the contact area and weakens the grasping effect (Fig. 2.32c). The *pattern of the serrations* determines the direction in which maximum resistance is obtained, i.e., the direction in which traction can be exerted with optimum effect (Fig. 2.33).

In *miniforceps* grooving also provides greater stability for a given cross-section of the closed instrument (Fig. 2.34).

The *ring forceps*, equivalent in principle to a circular serration, can exert traction in all directions (Fig. 2.35). The same principle is applied in *spoon forceps*, which add cuplike covers to the ring-shaped blades (Fig. 2.36).

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[20] Function is tested by a load test with material of known weight and surface roughness.

[21] Function is tested by visual inspection of the jaws as digital pressure is increased.

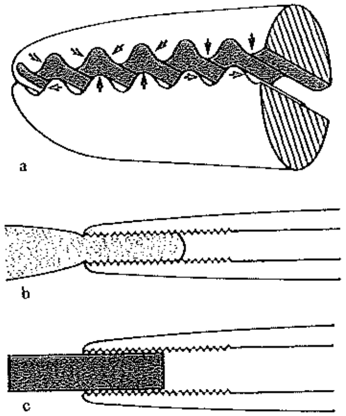


Fig. 2.32. **The principle of serration**

a Serration increases the contact area and changes the angles of attack at the substrate.

b This principle is effective on nonrigid material into which the serrations can "bite."

c On rigid material, only the tops of the serrations meet the substrate, so the contact area is actually reduced, and the varying angles of attack have no effect

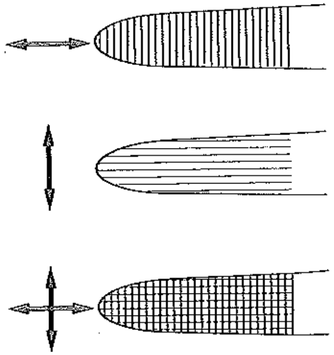


Fig. 2.33. **Directions in which serrations are most effective.** The ability to exert traction depends on the direction of the serrations. Cross-serrated jaws resist traction along the axis of the handle (*top*), while longitudinal serrations resist transverse traction (*center*). Criss-cross serrations can permit traction in all directions (*bottom*)

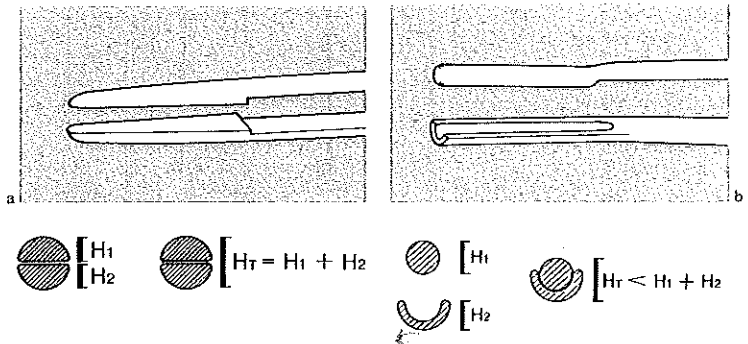


Fig. 2.34

a Miniforceps with smooth jaws: The stability of an individual blade is determined by its height *H*. The total height of the closed tip (H_T) equals the sum of the heights of the individual blades $H_1 + H_2$.

The grasping surface (*red*) is related to the diameter.

b Miniforceps with a single longitudinal groove: One blade is trough-shaped, the other cylindrical. Since the blades intermesh, the total height of the closed tip (H_T) is less than the sum of the blade heights. This can give greater stability than a forceps with smooth jaws (**a**) without increasing the height. The grasping surface is greater than in **a**, and the angles of attack at the substrate are variable

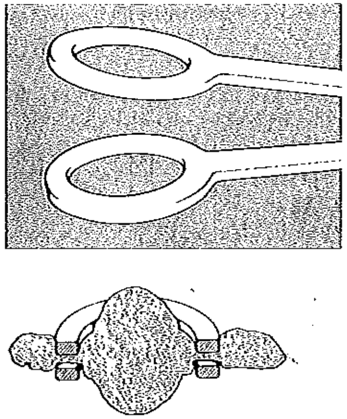


Fig. 2.35. **Ring forceps for soft material.** The material encompassed by the ring blades has a larger cross-section than the material compressed between the jaws. This keeps the tissue from shifting and thus permits traction in all directions. The small cross-section of the instrument allows passage through very narrow openings

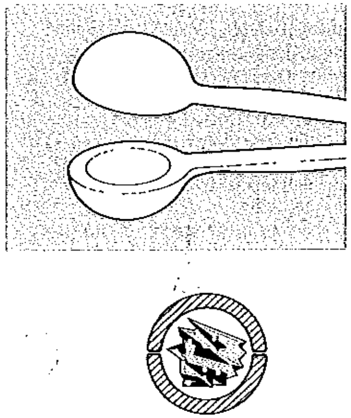
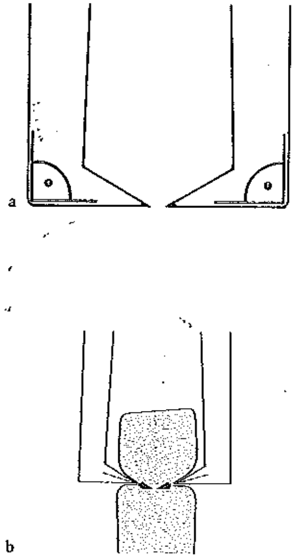


Fig. 2.36. **Spoon forceps for rigid material.** The grasping properties are similar to those of ring forceps, but the smooth outer surface protects surrounding tissues when manipulating particles with sharp edges. The cross-section is larger than that of ring forceps, so a relatively large access opening is needed for insertion into the eye

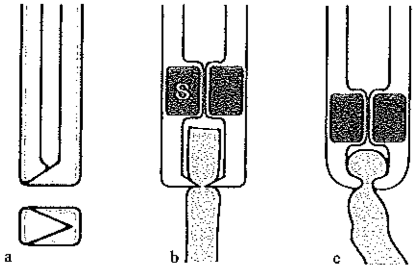


2.37

Fig. 2.37. **Straight teeth**

a In forceps with straight teeth (set at a 90° angle), the grasping vectors are directed inward.

b The vectors allow the forceps to grasp material lying *between* the blades



2.38

Fig. 2.38. **Straight-tooth forceps designs**

a Forceps with straight teeth can be engineered so that their outer surface is completely smooth when the jaws are closed.

b For tough material such as sclera or cornea, the teeth must be sharp enough to penetrate the tissue.

c For soft material such as iris or conjunctiva, blunt nonlacerating teeth may be used.
Stops (*S*) prevent tissue trauma

Toothed Forceps

Toothed forceps have a very small grasping area defined by the configuration of the teeth. This makes them suitable for precise "pinpoint" grasping. They exert a high pressure, however, and may damage delicate tissues.

Toothed forceps produce their grasping resistance chiefly by *surface deformation*. Their applications are determined by the force vectors of the teeth.

Forceps with **teeth at a 90 degree angle ("surgical forceps")** are, owing to the direction of the main vector, suited for grasping material that can be brought directly *between* the blades (Fig. 2.37). Since no vectors are directed outward, the outer surface of the forceps can be ground smooth so that it forms a blunt instrument when closed (Fig. 2.38a).[22] The *size and sharpness of the teeth* must conform to the thickness and quality of the tissue. Once the teeth have seized the tissue, the working motion is completed, and further action is limited to maintaining this position while the instrument is guided. Thus, complete closure of the jaws is not a criterion for grasping and can be prevented by *stops* as a precaution against tissue injury (Fig. 2.38b, c).

Forceps with **angled teeth ("mouse-tooth forceps")** have a forward-directed vector component (Fig. 2.39a), so the teeth can seize tissue lying *in front of the ends* of the blades. However, the forward vector component requires that a force of equal direction be applied during closure of the forceps, so the working motion is always coupled with a "*thrusting*" *forward motion.* This thrusting motion may encounter a high resistance if the teeth of the mouth-tooth forceps are not perfectly sharp. If the teeth are dull or bent, the forceps can at best be used as a surgical forceps (Fig. 2.39c). That is why mouse-tooth forceps require as much care in their manufacture and maintenance as cutting instruments.[23]

The function of the mouse-tooth forceps is analogous to that of a *claw*, *anchor*, or *trident* (Fig. 2.40), its various applications depending on the blade position when the instrument is applied:

As a *claw*, the forceps is able to grasp wound edges at an angle, with the advantage that the teeth bite more easily into the tissue than with ordinary surgical forceps. When used on smooth surfaces, it produces a fold.[24]

In its function as an *anchor*, the forceps grips a minimal amount of tissue and thus can grasp surfaces with a minimum of deformation.[25]

As a *trident* it can, without penetrating the tissue, produce a friction that can withstand weaker forces.[26]

The properties of toothed forceps can be combined with those of blunt grasping plates to create a *multipurpose forceps* in one instrument (Fig. 2.41).

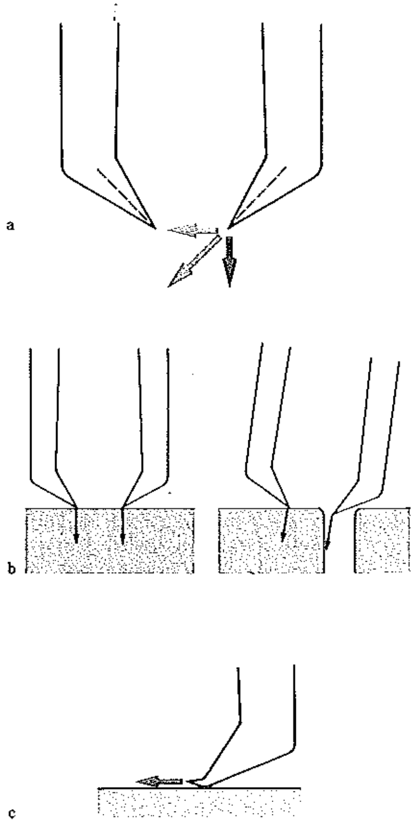


Fig. 2.39. **Angled teeth ("mouse teeth")**

a One component of the thrust vector is directed forward (*dark red*).

b Owing to the forward-directed vector, the teeth can penetrate material in front of the tips, such as a flat surface (*left*) or wound margin (*right*).

c Sharp teeth are easily bent by careless handling. This eliminates the forward-directed vector component at the tooth tip, and the teeth cannot bite into flat surfaces. The instrument then behaves as a forceps with straight teeth

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[22] Function is tested by running the fingertip along the undersurface of the closed blades.

[23] Function is tested by inspecting the tooth shape and watching for reflections at the tooth tip (a sign of dulling, see also footnote [29], p. 65).

[24] A typical example of the "claw" function is the grasping of a muscular insertion through the conjunctiva (see Fig. 3.25). Grasping the sclera creates a tissue fold that reduces the volume of the eye and raises the intraocular pressure.

[25] Unlike the claw, the anchor can grasp the sclera without raising a fold.

[26] This resistance is weak but may suffice for placing sutures with an extremely sharp needle. The trident configuration is advantageous in that the teeth need not penetrate the wound edges.

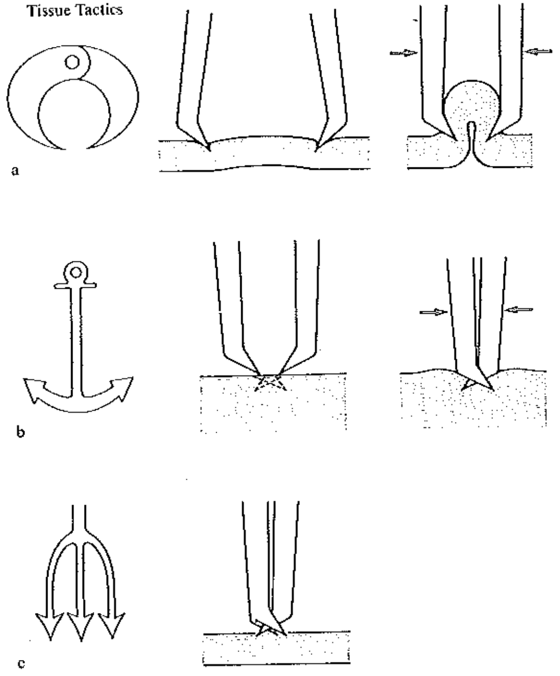

Fig. 2.40. Possible applications of mouse-tooth forceps

a Large blade opening: *Claw*. Closure of the blades produces a fold.

b Small blade opening (about one tooth width): *Anchor*. Note that the forceps must be perpendicular to the tissue surface for all the teeth to penetrate evenly.

c Blades closed: *Trident*. When closed, the teeth protrude to form the points of the "trident"

Tying Forceps

Tying forceps should have *rounded side edges* to avoid damage to delicate suture materials. The *tip*, however, should have *sharp edges* so that threads can be picked up from tissue surfaces (Fig. 2.42).

The forceps must be held properly to avoid suture damage. The *tip* area is used only for picking up the thread. If fine suture material cannot be grasped securely, the **blade closure** of the forceps should be checked. Complete closure may be prevented by a slightly *damaged tip* (Fig. 2.43a), by *incarcerated* foreign material (suture remnants, tissue debris, etc.) (Fig. 2.43b), or by overcompression of the handle (Fig. 2.43c).

For further handling the threads are passed over the rounded *side edges*, although these also can act as "cutting edges" if sudden or excessive traction is placed on the threads. When a thread is pulled tightly, therefore, it should not be stretched over sites having a small radius of curvature (Fig. 2.44).

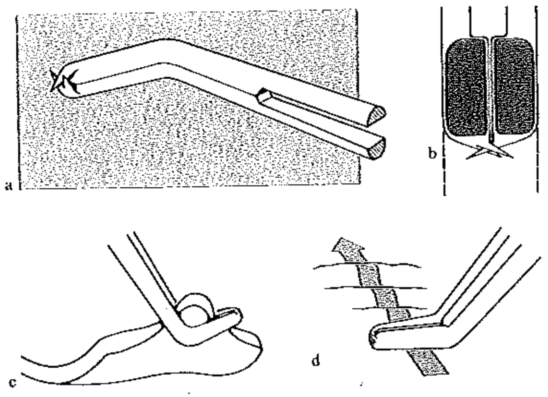

Fig. 2.41. Applications of a multi-purpose forceps

a Forceps with mouse teeth, grasping plates, and a handle angulated at the plates. The teeth can perform the claw, anchor, and trident functions described above.

b The grasping plates at the end of the forceps can be used for suture tying, provided they extend far enough laterally beyond the teeth to prevent fouling.

c The angulated grasping plates create "half-ring" blades that can apply traction to the edges of delicate tissue.

d When closed, the instrument can be used as a spatula

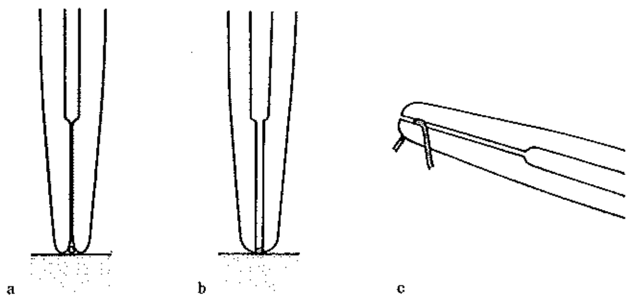

Fig. 2.42. Tying forceps

a Rounded tips cannot pick up a thin thread from a flat surface.

b The thread can be grasped only if the jaws meet as far as the tip (sharp edges).

c For handling, the thread is passed over the rounded side edges

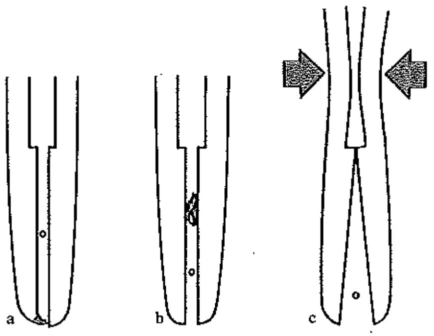

Fig. 2.43. Reasons for inability to grip fine suture material

a Damage to the sharp (vulnerable!) tip: A bent edge prevents the jaws from meeting.

b Closure is prevented by foreign material trapped between the blades.

c The jaws gape because of excessive pressure on the handle (see Fig. 2.31b)

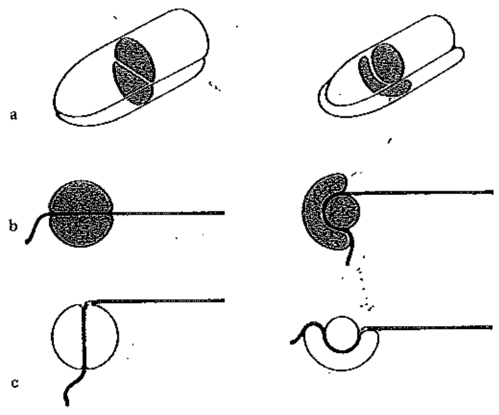

Fig. 2.44. Technique for holding tying forceps under a high suture tension. *Left*: Plane forceps. *Right*: Hollowed-blade forceps.

a Jaw configurations (cross-section: *Gray*).

b Risk of suture breakage is minimized by gripping the thread so that it passes over the largest radius of curvature.

c Risk of breakage is high when the thread is passed over sites where the radius of curvature is small (*red*)

Needleholders

If a needle is to pass through tissue, its *resistance* in the holder must be greater than in the tissue. Thus, a holder for use with heavy gauge needles that encounter high tissue resistance must be able to exert a *strong grip*, while a holder for fine, ultrasharp needles must be able to grip the wire *without damage*. When the needle is grasped, the only practical way to produce a sufficiently high frictional resistance is by applying a high pressure. However, there is a significant danger of needle slippage or deformation when a *high-pressure grip* is used.

The danger of **needle deformation** (bending or breaking) is lowest when the cross-sectional shape of the jaws conforms to the curvature of the needle (Fig. 2.45a). However, this means that each needle type would require its own needleholder for very high precision work. For practical reasons this solution is limited to cases in which very fine needles must overcome a relatively high resistance. Ordinarily, compromise designs are sought which permit a single needleholder to be used for multiple needle types (Figs. 2.45d, e and 2.46).

Slippage of the needle is likely to occur if the pressure is not applied at right angles to the needle shaft. This occurs in a diverging jaw opening (Fig. 2.47). It also occurs when the needle is gripped at an oblique angle to the jaw axis and therefore the shape of the jaws will determine the angles at which the needle can be held securely (Fig. 2.48).

The *appropriate construction* of a needleholder depends on the pressure that is to be exerted on the needle. The criteria are more stringent in cases where a high tissue resistance will be encountered than when an ultrasharp needle is passed through soft tissue.[27]

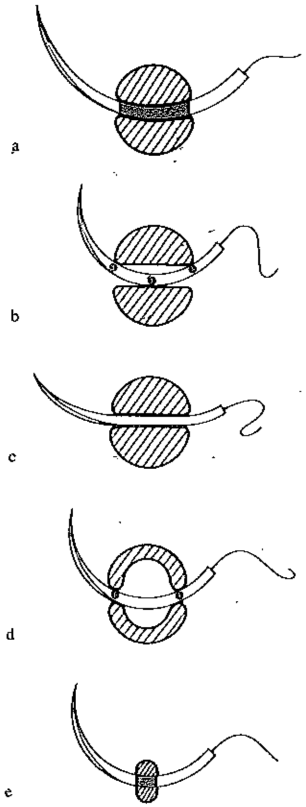

Fig. 2.45. **Cross-section of needleholder jaws**

a The curve of the jaws is congruent to the needle curve. The needle retains its shape even when gripped very tightly.

b Jaws with flat inner surfaces contact a curved needle at only three points.

c Closing the flat jaws will cause the needle to bend or break.

d Hollowed jaws make contact at only two points, so there is less danger of needle damage.

e With very fine, flat jaws, the lack of congruence between needle and jaws is negligible, and there is no danger of needle damage. Very fine jaws provide very little friction and therefore work only with ultrasharp needles that encounter minimal resistance in tissue

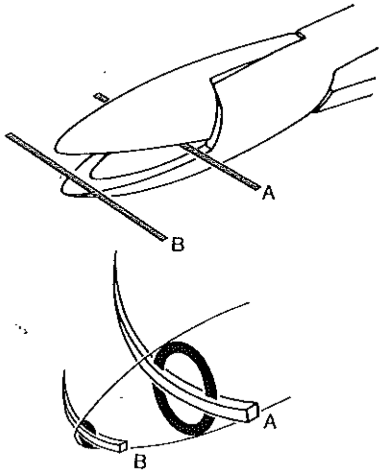

Fig. 2.46. **Multipurpose needleholder for grasping fine and heavier gauge needles.** The jaws have a conical outer shape (narrow at the tip and wider behind) with a deep inner groove.
Heavier gauge needles (*A*) are gripped in the rear part of the jaws close to the hinge (analogous to Fig. 2.45d).
Thin needles (*B*) are grasped with the tip of the jaws (analogous to Fig. 2.45e)

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[27] Needleholders for suturing the cornea must meet high precision requirements, while suturing of the conjunctiva may be done with a simple forceps.

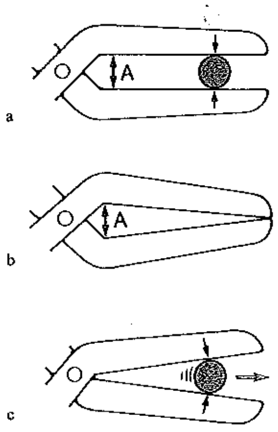


Fig. 2.47. **Direction of gripping vectors in a needleholder**

a When the jaws are parallel on gripping the needle, the forces are applied at right angles, and there are no force vectors that might shift the needle. Therefore the needle is held securely.

b Closure of the empty jaws in such a needleholder leaves a gap near the joint whose size (*A*) determines the needle gauge that can be held securely.

c If there is no gap, the jaws will diverge when gripping a needle, producing oblique force vectors that cause needle expulsion

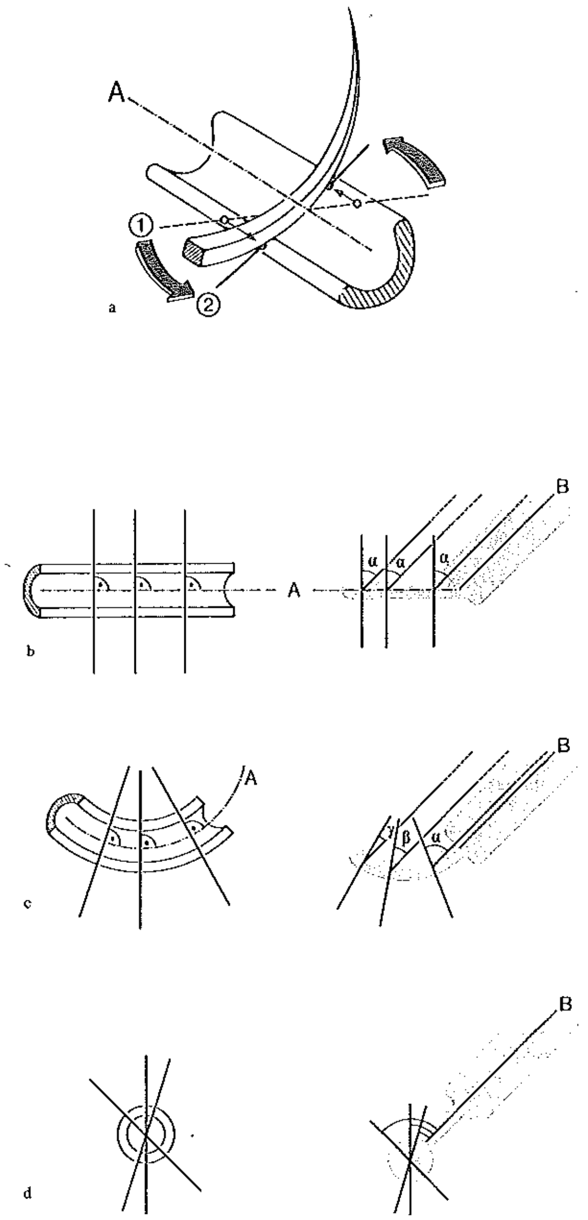
Fig. 2.48. **Angles between needle and axis ► of needleholder handle**

a When gripped obliquely (*1*), curved needles tend to shift until the distance between contact points is minimal, i.e., until they are perpendicular to the jaw axis *A* (*2*).

b In straight jaws there is just one angle at which the needle can be gripped. That is the angle (α) between the jaw axis (*A*) and handle axis (*B*).

c In curved jaws the needle can be gripped at various angles (α, β, γ) to the handle axis. However, the needle must be held at different places in the jaws for each of the various angles to that it will stay perpendicular to the curved jaw axis (*A*).

d In hemispheric jaws (spoon forceps with a "point" axis, see also Fig. 2.36), the distances between contact points are equal in all directions, so the needle can be gripped at any desired angle to the handle axis



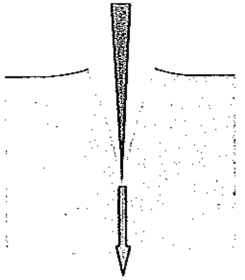


Fig. 2.49. **Cutting.** Tissue fibers are divided by a highly concentrated pressure (pressure of the cutting edge and counterpressure of the tissue). The properties of the cutting edge determine the quality of the result. The movement of the cutting edge controls the direction in which the tissue is divided

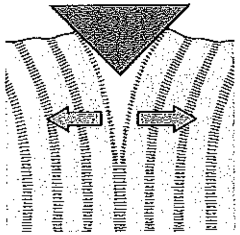


Fig. 2.50. **Splitting (blunt dissection).** Splitting is rupturing, accomplished by driving a wedge into a preexisting tissue space. The effect depends on the width of the wedge (which determines the force of the dissection) and the properties of the tissue (which define the path of least resistance). The leading edge of the wedge does not touch the fibers to be divided

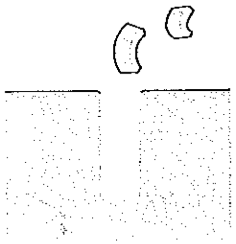


Fig. 2.51. **Division of tissue by removal of material.** The tissue is divided by excavating a "channel" through it

2.1.3 The Division of Tissues

General Techniques

Tissues can be divided by *cutting, splitting*, or by the *removal of material*. In **cutting**, the tissue fibers are divided by a direct and concentrated application of pressure. This procedure divides only fibers coming in contact with the cutting edge ("sharp dissection") (Fig. 2.49), so the surgeon can precisely control the cutting process by guidance of the cutting edge.[28]

In division by **splitting** ("blunt dissection"), the tissue fibers are overstretched to the point of rupture. This technique is effective only in *preformed tissue spaces* that provide anatomic paths of low resistance. The split is accomplished by means of a wedge (Fig. 2.50), which forces the more resistant layers apart while causing the loose intervening fibers to rupture without touching them directly. Thus, the properties of the cutting edge are important only in locating a suitable level at which to initiate the split and do not affect the splitting process itself. The latter, incidentally, is not controlled by the shape or movement of the wedge but depends chiefly on the anatomy of the interspaces between firmer tissues. Splitting is appropriate, then, when the surgeon wishes to be guided by the properties of the tissue itself, without "imposing his will upon it."

The **removal of material** lying between the parts to be divided (Fig. 2.51) is the basic principle of division by *sawing, drilling*, and *burning*. When the divided parts are reunited, the tissue cannot be fully restored to its anatomic state because of the lost material. Therefore, such techniques generally are used in ophthalmic surgery only if the goal of the operation is *dehiscence*.

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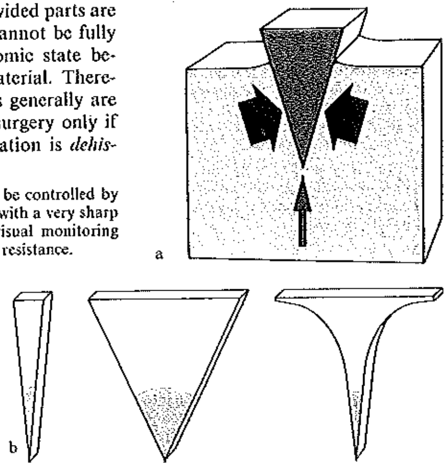
[28] Whereas splitting can be controlled by tactile feedback, cutting with a very sharp edge relies on perfect visual monitoring because of the low tissue resistance.

Fig. 2.52. **The "cutting ability" of an instrument**

a A cutting instrument consists of a cutting edge and its carrier. The resistance to the cutting edge (*red arrow*) determines the actual cutting ability of the instrument, while the resistance to the carrier (lateral resistance, *black arrows*) determines the ability of the instrument to penetrate into tissue.

b The narrower the wedge, the lower the lateral resistance, but the lower the blade stability as well. The concave blade (*right*) combines high sharpness (low lateral resistance) with high stability (broad back)



Special Problems in Cutting

While in theory the line of an incision should follow the exact path on which the surgeon guides the cutting edge, in reality significant deviations occur. However, by knowing the factors that alter the path taken by a cutting instrument through tissue, the surgeon can incorporate the factors into his operating plan and still achieve the desired precision. These factors are: the shape of the **instrument**, the properties of the **tissue**, and the guidance of the instrument by the **surgeon**. All these factors play a role in determining the facility with which the tissue is divided ("*sharpness*") and the path that the cutting edge follows in the tissue (*the shape of the cut*).

Sharpness is a product of the *cutting ability* of the instrument and the *sectility* of the tissue.

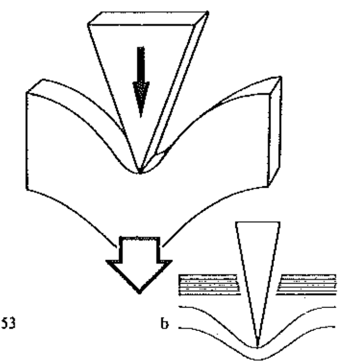
The **cutting ability of instruments** (Fig. 2.52) is determined largely by the cutting edge. If the edge is a geometric point or line (with "zero surface area"), the pressure becomes infinitely high when any force is applied, and the resistance at the edge, (i.e., the *cutting resistance* proper) becomes infinitely low.[29] Additionally, cutting ability is influenced by the carrier, or the part of the instrument that holds the cutting edge. The resistance encountered by the carrier, called the *lateral resistance*, depends on the angle formed by the carrier surfaces (Fig. 2.52b).

The **sectility of tissue** depends on the tendency of the fibers to be severed rather than displaced by an advancing blade (Fig. 2.53a). If the sectility is low, even a sharp blade will seem dull. If a blade is passed through tissue layers of *varying sectility*, only the layers with high sectility are cut while those of low sectility may remain intact (Fig. 2.53b).

Fig. 2.53. **The "sectility" of tissues**

a Tissue that is very mobile tends to shift ahead of the blade and is not sectioned.

b Practical importance of sectility: If a cutting edge is advanced through successive tissue layers of different sectility, it may divide the layer with high sectility while pushing aside the layer with low sectility



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Sectility can be enhanced by any means that keep the tissue from shifting ahead of the cutting edge (Fig. 2.54):

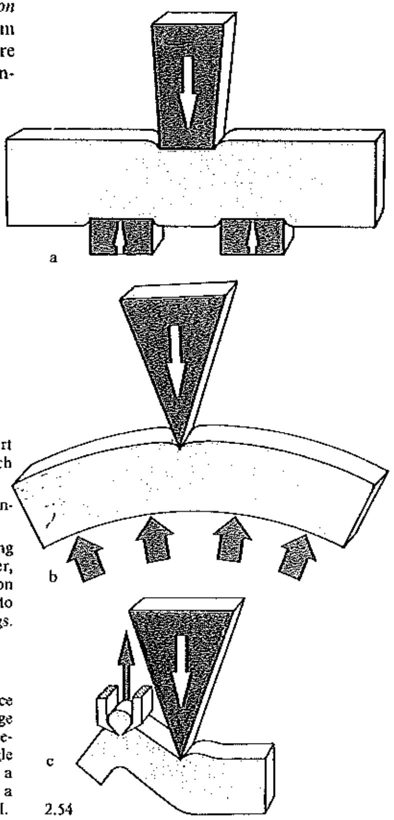
Counterpressure may be provided by mechanical supports – the principle employed in scissors and punches. Increased *tissue tension* also prevents tissue fibers from shifting. Hard eyes, therefore, are more sectile than soft ones. Coun-

Fig. 2.54. **Methods of improving sectility**

a The jaws of the instrument can support the material from below (here: The punch principle).

b Tissue tension is increased by a high intraocular pressure.

c Tissue tension can be varied by applying countertraction with a forceps. However, this method may cause tissue deformation requiring corrective blade movements to obtain the intended cut (see also Figs. 5.78, 5.81c)



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[29] Function test: The absence of surface area on a properly ground cutting edge is evidenced visually by the absence of reflections from it, regardless of the angle of light incidence. A light reflex on a ground edge signifies that the edge has a definite surface area and therefore is dull.

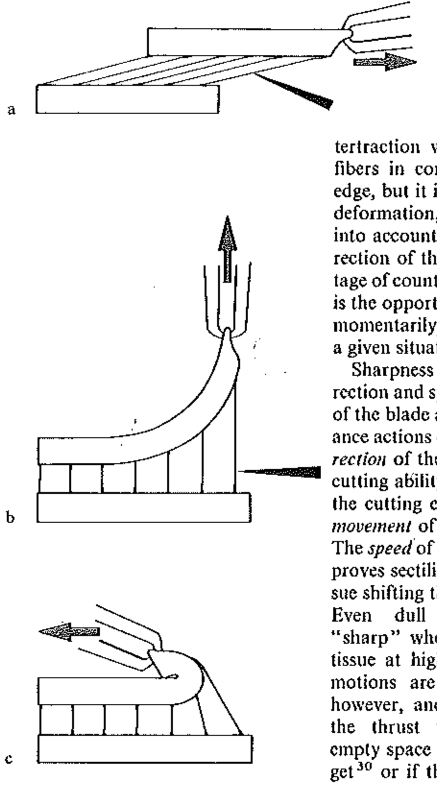

Fig. 2.55. **Use of forceps traction to control sectility in the sharp dissection of tissue layers**

a Diffuse tension: Forceps traction parallel to the tissue surface tenses all fibers along the plane of the dissection; The resistance to the forceps traction is correspondingly high. The sectility of all fibers is increased equally.

b Progressive tension: Perpendicular traction elevates the overlying layer, and the fibers that present to the cutting edge are tensed in progressive fashion. Only the sectility in that zone is increased.

c Selective tension: Reflecting the layer to be dissected restricts tension selectively to the target fibers. The other fibers are less sectile and are protected from inadvertent damage. Because the necessary tension is transmitted to only a few fibers, resistance to the forceps traction is low

tertraction with *forceps* keeps the fibers in contact with the cutting edge, but it invariably causes tissue deformation, which must be taken into account when deciding the direction of the cut. A major advantage of countertraction with forceps is the opportunity to adapt sectility momentarily to the requirements of a given situation (Fig. 2.55).

Sharpness also depends on the direction and speed of the movements of the blade and hence on the guidance actions of the surgeon. The *direction* of the movements increases cutting ability when it is parallel to the cutting edge (a "*pull-through*" *movement* of the blade) (Fig. 2.56). The *speed* of the cutting motion improves sectility because it limits tissue shifting through inertial effects. Even dull blades may seem "sharp" when thrust through the tissue at high speed. Rapid blade motions are difficult to control, however, and are safe only when the thrust vectors terminate in empty space after reaching the target[30] or if their magnitude is limited by the instrument design.[31]

The **shape of the finished cut** is determined by the path taken by the cutting edge through the tissue. It might be assumed that the cutting path would match the path on which the surgeon guides the cutting edge (the *guidance path*). But in reality the two paths coincide only under certain conditions, i.e., when the advancing blade cannot push the tissue aside. Otherwise the cut will deviate, and the result will not conform precisely to the surgeon's intent (Fig. 2.57).

Deviations of the cutting path from the guidance path are the result of *asymmetric resistances* in the tissue. As the cutting edge advances, this asymmetry forces the tissue in the direction of the higher resistance. In other words, tissue from the side with the lower resistance "piles up" ahead of the blade, and the cut deviates in the direction of the lower resistance.

If a very precise cut is required, these tendencies must be taken into account when formulating the operating plan. Specifically, the causes of asymmetric resistances must be analyzed as they relate to the design of the instrument, the guidance of

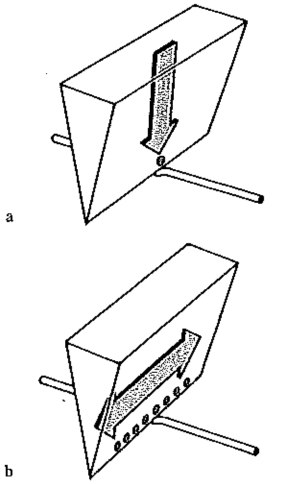

Fig. 2.56. **Concept of the "pull-through" cutting action**

a With a simple thrusting action of the blade, each tissue fiber encounters a single point on the cutting edge (the cutting point, *red*). This action drives the cutting edge into deeper layers, and the cut progresses in depth.

b If the blade is moved parallel to the cutting edge, each fiber is successively exposed to the action of multiple cutting points. This improves cutting ability without deepening the cut

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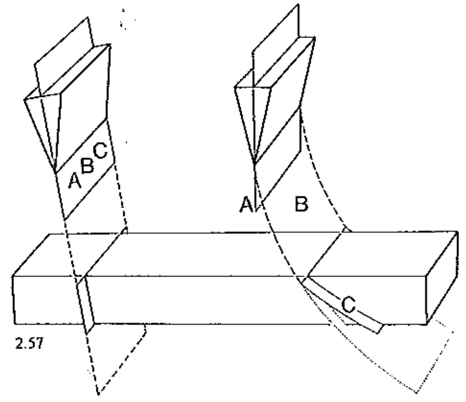
[30] Examples: Needles, cataract knives.

[31] Examples: Vibrating knives, ultrasonic vibrating probes.



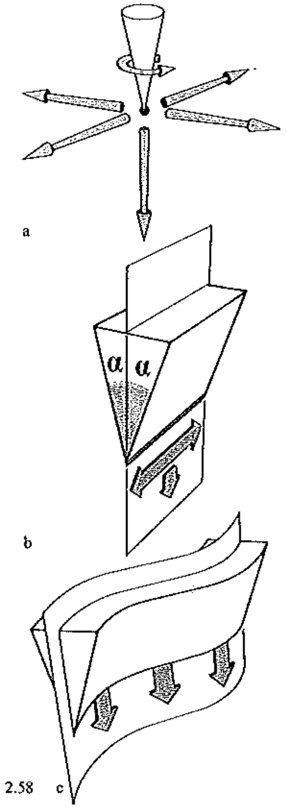
2.57

Fig. 2.57. **Analysis of the cutting process in terms of preferential path, guidance path, and path in the tissue.** The three factors – instrument, surgeon, and tissue – are characterized by three geometric surfaces:

Preferential path (*A*): The path the instrument tends to follow by virtue of its construction.
Guidance path (*B*): The actual path of the cutting edge as directed by the surgeon, characterizing his intent.
Path in the tissue (C): The result of the cutting process: the cut surface.

Ideally (*left*) all three surfaces coincide, and the cut surface matches the surgeon's intent. In reality (*right*), the surfaces usually do not coincide because

- the guidance path does not equal the preferential path if the surgeon does not guide the cutting edge precisely along the bisector of the carrier surfaces;
- the path in the tissue does not equal the guidance path if the tissue shifts ahead of the cutting edge



2.58

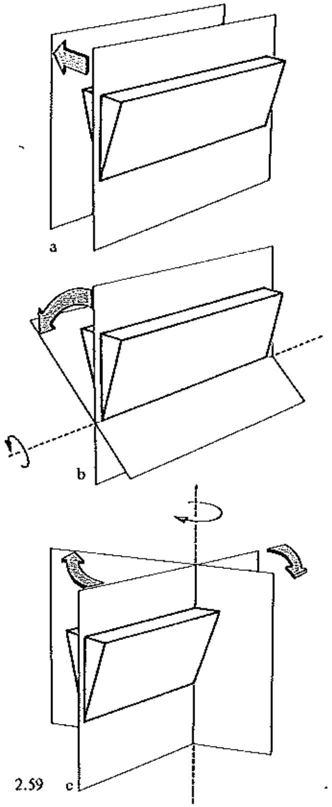
Fig. 2.58. **Motions with symmetrical lateral resistance**

a A single, imaginary cutting point has unlimited mobility. That of a real cutting point is limited by the lateral resistance of its carrier.

b A linear cutting edge describes an imaginary surface as it moves. If the lateral resistance is symmetrical, its motion follows the bisector of the carrier surfaces (the "preferential path"). If this path is a plane (knife) or the surface of a body of revolution (trephine), there are two motions with a symmetrical lateral resistance (*arrows*):

- motion perpendicular to the cutting edge (thrusting; see Fig. 2.56a);
- motion parallel to the cutting edge (pull-through; see Fig. 2.56b).

c If the preferential path is a surface of irregular curvature, the only motion with a symmetrical lateral resistance is thrusting, since any pull-through motion will create vectors perpendicular to the preferential path. Blades of this shape are useful only in punch-like mechanisms



2.59

Fig. 2.59. **Motions with asymmetrical lateral resistance.** Any motion of the blade that does not follow the preferential path creates vector components perpendicular to the preferential path, resulting in asymmetrical lateral resistances. This can result from lateral shifting of the blade (a), rotation about the axis of the cutting edge (b, see also Fig. 2.74), or rotation about an axis perpendicular to the cutting edge (c, see also Fig. 2.75)

the instrument, and the properties of the tissue.

The path on which the blade encounters symmetric lateral resistances in the tissue is called the *preferential path* of the cutting edge. It lies on a plane that bisects the lateral surfaces of the carrier. This imaginary plane does not represent an actual carrier surface[32] but simply characterizes the path a blade tends to follow by virtue of its design. The motion vectors on the preferential path can be resolved into components perpendicular to the cutting edge (*thrust vectors*) and components parallel to the cutting edge (*pull-through vectors*) (Fig. 2.58). If a blade is not guided precisely along its preferential path, the *lateral resistance* will become *asymmetrical*, increasing on one side of the blade and dwindling on the opposite side (Fig. 2.59).

This has two consequences: First, the cutting instrument is forced back toward the preferential path by the tissue. If the surgeon wishes to keep the blade on the path initiated, he must apply greater force. Second, the tissue fibers ahead of the blade are pushed toward the side of greater resistance, causing the finished cut to deviate toward the side of lesser resistance (Fig. 2.60).[33]

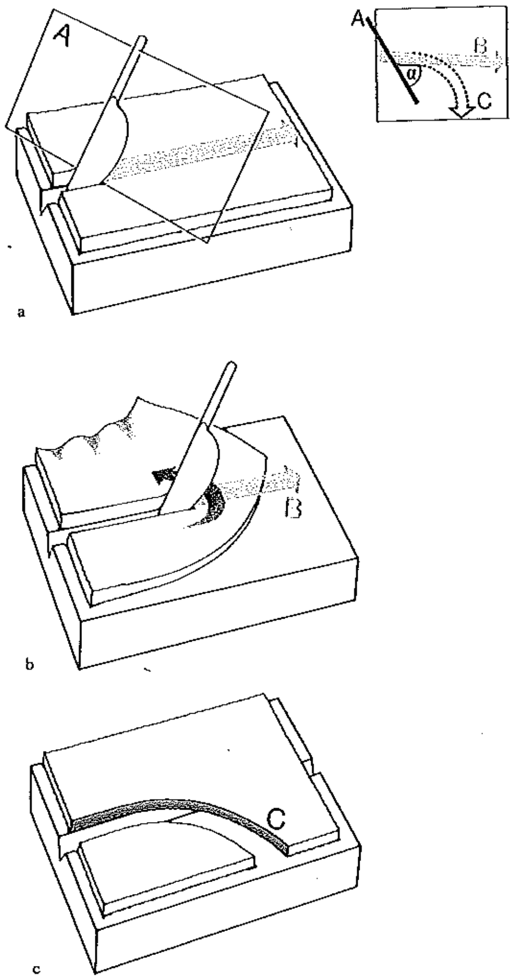


Fig. 2.60. **Deviation of the cut due to asymmetrical lateral resistance.** If the blade is maneuvered so that the guidance path (*B*) forms an angle with the preferential path (*A*), the path in the tissue (*C*) deviates from the intended direction (*inset*) and tends increasingly to follow the preferential path (where the lateral resistance is again symmetrical).

a Blade guided at an angle to the preferential path (outlined in *red*).

b The tissue ahead of the cutting edge shifts toward the side with the higher resistance.

c The finished cut deviates toward the side of the lower resistance

It follows, then, that the *precision* of a cut is greatest when the guidance path (of the surgeon) is congruent with the preferential path (of the instrument).[34] In practical terms this means that when the surgeon wishes to direct the blade *along the preferential path* (of the instrument), it is helpful to maximize the lateral resistance (either by selection of the blade shape or the manner of holding the blade), for this makes it easier to continue the cut in a given direction and reduces the danger of inadvertent deviations (Fig. 2.74).

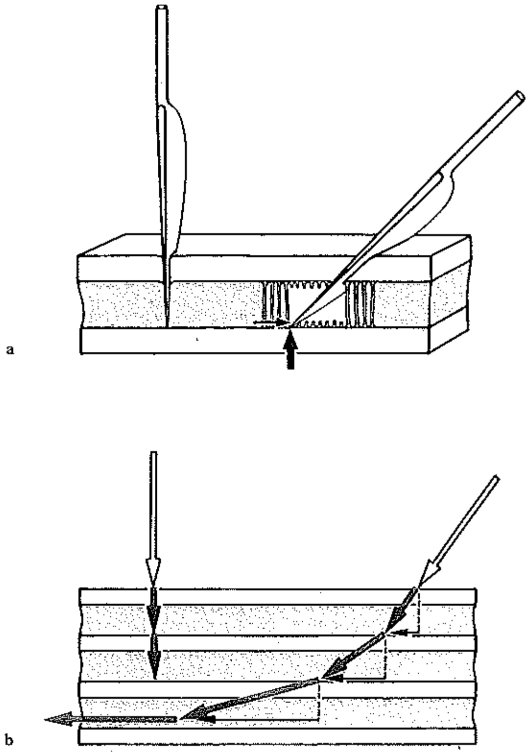


Fig. 2.61. **Lamellar deflection.** a Position of blade, **b** path in the lamellae. Lamellar tissues consist of a regular arrangement of layers with varying resistances. A blade directed through the layers at a right angle (*left*) encounters a symmetrical lateral resistance and can advance in the intended direction. If the cut is started obliquely (*right*), the lateral resistance is asymmetrical because it is higher at the lamellae than in the interlamellar space. The path in the tissue deviates more and more until it terminates parallel to the lamellae in an interlamellar layer, where lateral resistance is again symmetrical

If the cutting edge is *not guided along its preferential path*, as when curved incisions must be made for which there is no congruent blade, it is necessary to cope with the problems of an asymmetric lateral resistance. These problems can be reduced by making the lateral resistance as low as possible. This is done by selecting a blade with a small carrier surface and guiding it so that only a small part of the blade enters the tissue (see Fig. 2.74).

The second major source of asymmetric lateral resistances is in the tissue, the causes being either the structure of the tissue itself (*nonhomogeneities*) or external *stresses* imposed on the tissue by the surgeon. Both cause incisions to deviate in typical, predictable ways.

In **lamellar tissues**, for example, the resistance to a cutting edge is lower in the direction of the lamination than at right angles to it. As a result, the incision is progressively deflected onto a path parallel to the tissue layers (Fig. 2.61). The surgeon can influence the tendency toward *lamellar deflection* by regulating the effective "sharpness" of the cut. *Blunt* cutting conditions (i.e., low cutting ability of the blade combined with low sectility of the tissue) promote lamellar deflection and are advantageous when the surgical goal is the dissection of tissue *layers*.[35] *Sharp* cutting conditions are advantageous when it is necessary to cut *across the lamellae*.[36]

Other typical sectile characteristics are found in **compliant, resilient tissues.** When these tissues are under uniform tension, they tend to be pushed forward by the blade (Fig. 2.62) so that the resulting incision is shorter than the distance traveled by the cutting edge.[37] Consequently, the cutting movement must be carried past the target to obtain an incision of the desired length.

When compliant, resilient tissue is under *asymmetric tension*, it tends

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[32] If the cutting edge is a point, the preferential path of the instrument is a geometric line.

[33] When the surgeon becomes aware by tactile feedback that greater force is needed to keep the blade on the initiated path, he may assume that deviation is occurring.

[34] Examples: A plane guidance path for cataract knives and keratomes, a cylindrical guidance path for trephines.

[35] Example: Lowering the intraocular pressure by medication or by puncture of the anterior chamber in lamellar corneal grafting.

[36] Example: If the anterior chamber must be opened when the intraocular pressure is low, lamellar deflection can prevent the blade from reaching the anterior chamber at all. Therefore the intraocular pressure must be raised.

[37] This explains why penetrating foreign bodies "cut" openings that are smaller than their own diameter. Extraction of the foreign body usually necessitates extension of the entry wound.

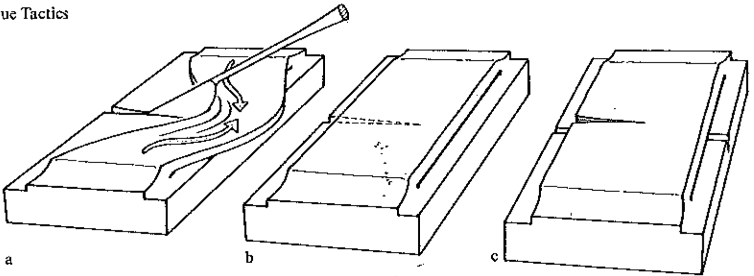

Fig. 2.62. **Forward shifting tendency.** In the model, a mobile tissue layer loosely overlies a substrate of firm tissue. The layers are adherent to each other in the gray zones.

a The loose tissue layer is shifted ahead of the blade.

b With a short cutting stroke, the length of the incision in the firm sublayer equals the distance traveled by the cutting edge, but the mobile layer remains intact (see also Fig. 2.53).

c A longer cutting stroke incises the mobile layer as well, but the incision is shorter than the distance traveled by the blade.

Note: When symmetrical tissue tension is present, the cut follows the direction of the guidance path

to shift also laterally, causing the cut to deviate toward the side of lesser tension (Fig. 2.63). This asymmetry of tensions is encountered whenever loose tissue is fixed on one side, whether anatomically,[38] by scar tissue, or by the surgeon himself with fixation instruments.

These shifting tendencies can be reduced by making the tissue tense before cutting, thereby increasing its sectility. However, this introduces yet another mechanism which may cause the cut to deviate from the guidance path: **tissue retraction.** Compliant, resilient tissue will temporarily elongate when tension is applied to it. Releasing the tension restores the tissue to its former shape, and all distances are again shortened in proportion to the initial degree of stretch (Fig. 2.64). *Incisions* made in the stretched tissue are shifted from their original position toward the zone of fixation,[39] and excisional defects are diminished in area. This *retractile tendency* may become a source of unanticipated changes in the shape and location of incisions, but it can also be exploited to achieve specific goals.[40]

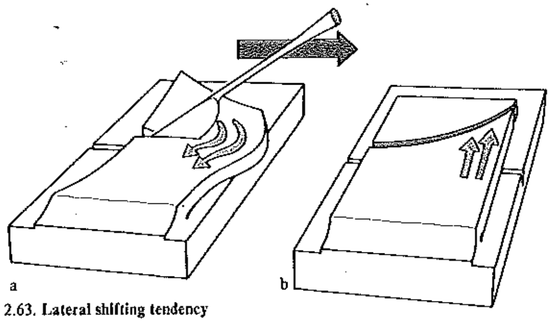

Fig. 2.63. **Lateral shifting tendency**

a If tensions on the tissue are asymmetrical, the mobile tissue will shift ahead of the cutting edge toward the side of higher tension, i.e., toward the zone of fixation (*gray*).

b The resulting incision in the mobile layer deviates toward the opposite side, away from the zone of fixation. In contrast the incision in the firm layer coincides with the guidance path

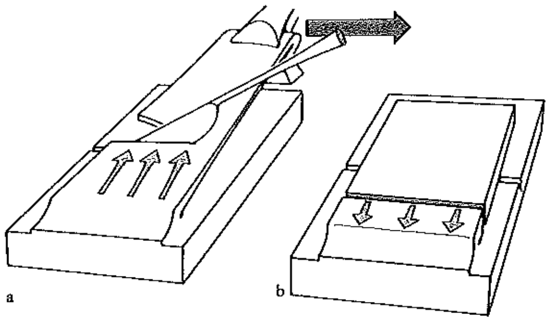

Fig. 2.64. **Tendency of retraction.** If the tissue is divided while stretched **(a)**, the resulting incision will shift toward the zone of fixation after the tension is released **(b)**

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[38] Example: Fixation of the conjunctiva at the limbus, fixation of the iris at the iris root.

[39] Example: Shifting of incisions toward the limbus or iris root.

Blades with a Point Cutting Edge

Owing to their great freedom of movement, "point" cutting edges (Fig. 2.65) can produce *incisions of any shape* desired. The preferential path of the instrument and the guidance paths are identical in all directions, and an incision is made wherever the point of the blade is directed (Fig. 2.66). A two-dimensional effect can be achieved by making a series of closely spaced linear cuts (Fig. 2.67).

However, as soon as the blade penetrates more deeply into the tissue, the *shape of the carrier* becomes a factor, and lateral resistance is introduced. If the carrier is *conical*, this resistance is equal in all directions (Fig. 2.58a). If the carrier is *prismatic*, the resistance depends on the position of the largest carrier cross-section relative to the guidance direction (Fig. 2.68). By rotating the blade, then, the surgeon can vary the resistance and modify the "sharpness" of the blade as needed (Figs. 2.69, 2.70).

Blades with a point cutting edge are extremely versatile cutting instruments, but they are also very delicate and subject to rapid wear. That is why the blades are constructed of material that is highly wear-resistant (diamond) or easily replaced (razor blade fragments).[41]

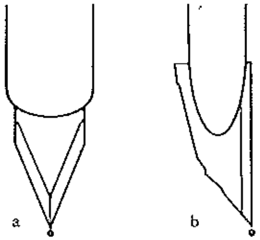

Fig. 2.65. **Blades with a "point cutting edge"**

a Diamond knife.

b Razor blade fragment in a holder

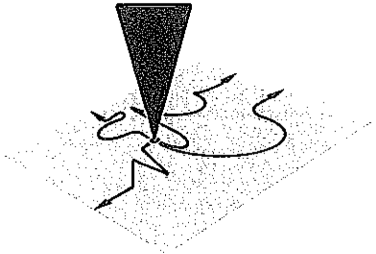

Fig. 2.66. **Cutting characteristics of a point cutting edge.** If only the sharp point of the blade cuts the tissue (i.e., if the blade does not penetrate so deeply that the shape of the carrier becomes a factor), the lateral resistance is symmetrical in all directions, and the number of preferential paths is infinitely large. Cutting conditions are ideal in almost all guidance directions, i.e., the preferential path and guidance path are congruent. The surgeon can use the point cutting edge like a pencil to "draw" an incised line of arbitrary shape

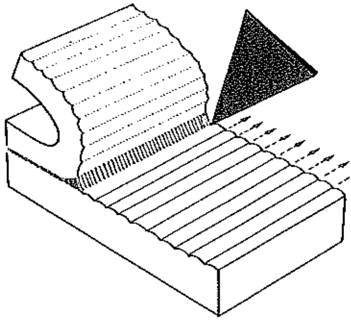

Fig. 2.67. **Technique of using a point cutting edge.** A plane of sharp dissection can be established by making a series of closely spaced linear incisions. The resulting cut surface has a "hatched" appearance

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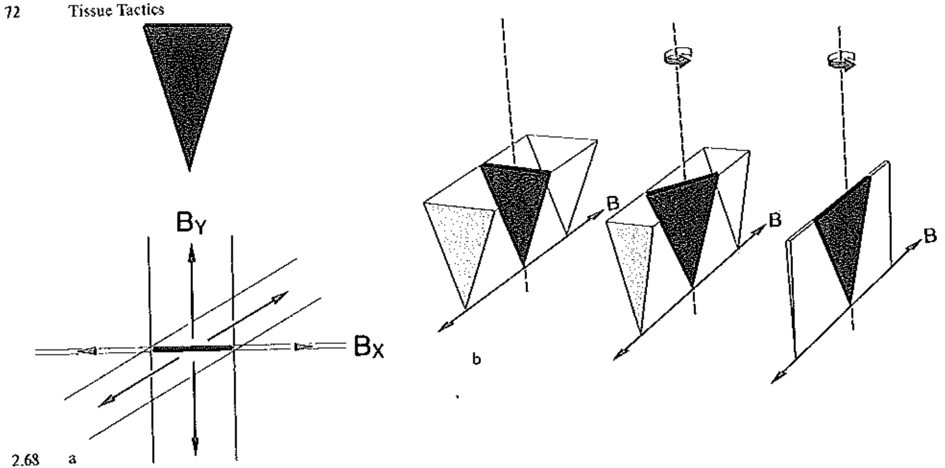
[40] Example: Excising the iris very close to its base when making a peripheral iridectomy (see Fig. 7.21a).

[41] Only if the point cutting edges are used exclusively in the "thrusting" mode, such as the points of keratomes, cataract knifes or needles, the problem of wear is reduced.



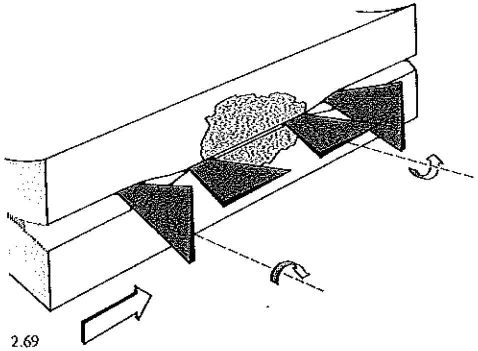
2.68 a

b

Fig. 2.68. **Lateral resistance of blades with a point cutting edge**

a With a prismatic carrier, the lateral resistance increases with the width of the blade surface projected in the guidance direction. Thus, lateral resistance is maximal when the widest blade surface is perpendicular to the guidance direction (B_y) and minimal when the widest blade surface is parallel to the guidance direction (B_x).

b Lateral resistance can be changed from maximal (*left*) to minimal (*right*) simply by rotating the blade. *B*: Guidance direction



2.69

Fig. 2.69. **Modifying the lateral resistance, illustrated for the dissection of lamellae fused by scar tissue.** The blade is kept on the interlamellar plane by directing it in "blunt" fashion (see Fig. 2.68b, *left*). To overcome the higher and irregular resistance of the scar (*gray*), the blade is rotated into a "sharp" position (see Fig. 2.68b, *right*)

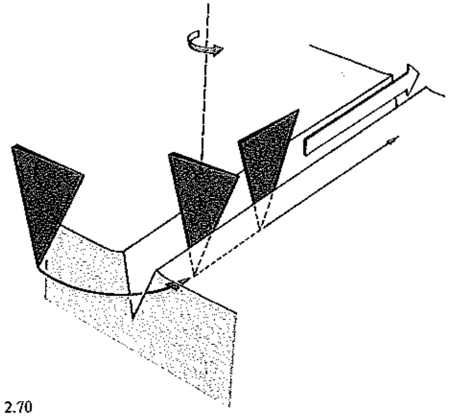


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Fig. 2.70. **Modifying the lateral resistance, illustrated for inserting a blade into a precut groove.** The blade needs to be inserted so that the cutting edge will reach the base of the groove without injuring the walls. This is done by holding the blade with its broadest surface perpendicular to the guidance direction, thereby decreasing its effective sharpness. At the base of the groove, maximal sharpness is needed to deepen the incision, so the blade is rotated until its broadest surface is parallel to the guidance direction (*red arrow*)

Knives with a Linear Cutting Edge

Knives are characterized by a linear cutting edge. Different blade configurations (Fig. 2.71) differ in the *longitudinal profile* of the cutting edge, which determines the angle at which each cutting point attacks the tissue (Fig. 2.72), and also in the shape of the *carrier surfaces*, which determines the lateral resistance (Fig. 2.73).

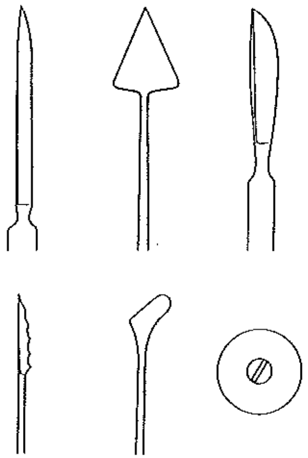


Fig. 2.71. **Knives with linear cutting edges.** *Top row*: Cataract knife, keratoma, scalpel. *Bottom row*: Serrated knife, hockey knife, circular knife

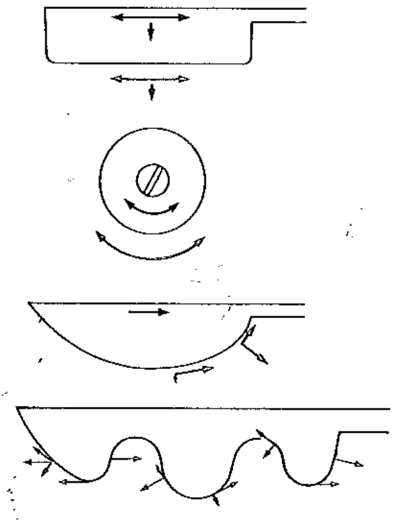


Fig. 2.72. **Attack angles of various blades.** A pure thrusting motion is possible only with a straight, linear cutting edge; a pure pull-through motion can be made with straight as well as circular edges. For all other edge shapes, every blade motion produces a combination of both vectors. In the serrated edge (*bottom*), this principle is exploited most fully to maximize the cutting ability of the blade

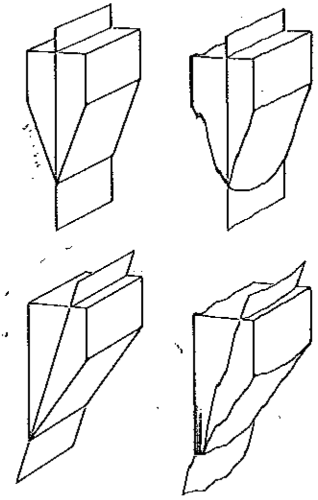


Fig. 2.73. **Preferential paths of linear blades**
Top row: All symmetrically ground blades have a plane preferential path regardless of the shape of the cutting edge.
Bottom row: Asymmetrically ground blades have a plane preferential path only if the cutting edge is straight. This path is off-angle to the main carrier axis, however, and if the edge is directed along this axis, it will encounter an asymmetrical lateral resistance (*left*). Asymmetrical blades with a curved cutting edge differ from simple knifes in that their preferential path is arched (*right*). This is not a problem if the blade is used at tissue surfaces, but if it penetrates more deeply the cutting properties become complex

When the lateral resistances on the blade are symmetrical, the resulting cut surface is a *plane*. A straight incision, then, is obtained by holding the blade such that a maximum amount of blade surface comes between the edges of the incision. For a curved incision, on the other hand, only a small amount of blade surface should penetrate the tissue (Fig. 2.74). When the direction of the incision is changed, the smoothest cut surfaces are obtained by turning the blade so that the cutting edge itself forms the axis of rotation (Fig. 2.75).

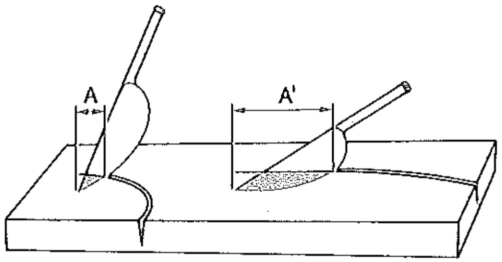


Fig. 2.74. **Blade position for making curved incisions.** To obtain a curved cut surface that differs in shape from the plane preferential path, lateral resistance must be minimized. *Left*: An upright blade position decreases lateral resistance and allows the incision to be curved. *Right*: A low blade position tends to produce a straighter cut. *A*, *A'* length of blade immersed in tissue

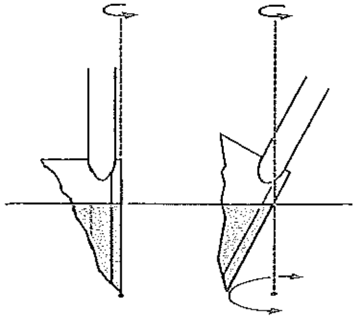


Fig. 2.75. **Axis of rotation for direction changes.** If the cutting edge itself forms the axis of rotation, a smooth cut surface is produced (*left*). But if the cutting edge is off the axis, each cutting point has a different radius of rotation, and an irregular cut surface is obtained (*right*)

Scissors

The cutting properties of *scissors* are quite complex in that the combination of two blades does not simply represent the sum of their individual cutting properties but forms an entirely new instrument with unique characteristics (Fig. 2.76).

A scissors can divide tissue in three different ways:

- by closing the blades
- by opening the blades
- with the tip of the blades.

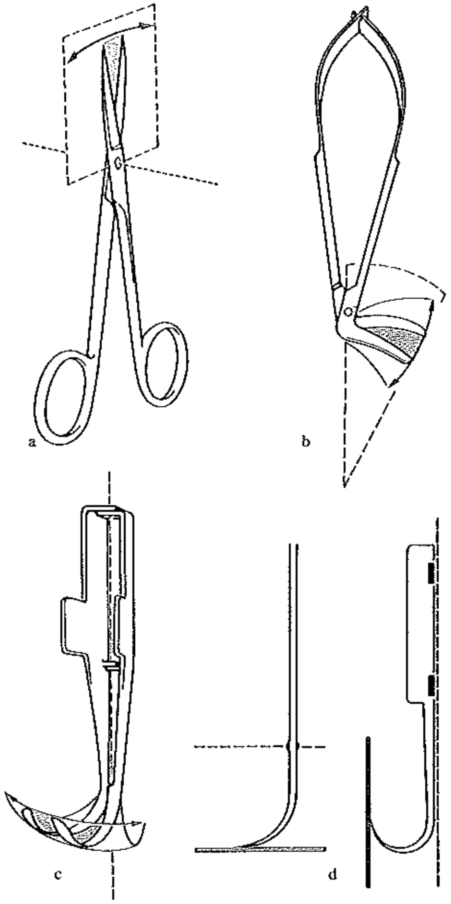


Fig. 2.76. **Types of scissors.** A scissors consists of two opposing blades connected by a screw joint. The handles and blades can be combined in various ways. The position of the joint determines the maximum allowable blade curvature. The guidance path (on which the cutting edges are guided during the working motion) is determined and constrained by the construction of the instrument. *White areas outlined in red*: Guidance path of blades during opening. *Red area between the blades*: Guidance path during closure. *Arrow*: Guidance line of blade tips.

a Straight scissors with ringed handles and simple screw joint. The guidance path is plane.

b Angled, curved scissors with a spring handle. The guidance path is the surface of a cone.

c Hinge-handle scissors with deeply curved blades.

d Relation between blade curvature and joint position. The blade curve is the maximum possible when the tangent to the blade tip (*red line*) is parallel to the joint axis (*broken line*). At greater curvature the blade tips will meet before the scissors is completely closed. With a simple screw joint, the maximum allowable curvature is 90° (*left*); with a hinge handle, 180° (*right*)

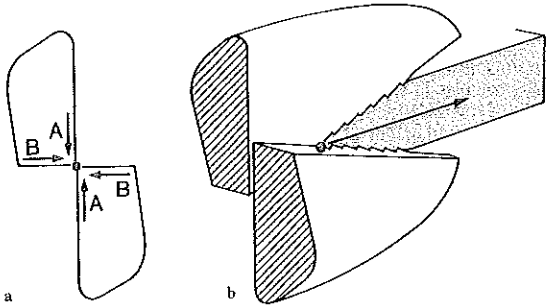


Fig. 2.77. **Principle of cutting by closure of the scissors**

a The ground edges of the blades meet at the cutting point, formed by vector component *A* perpendicular to the joint axis (closing motion of scissors) and vector component *B* parallel to the joint axis (shearing stress).

b The cutting point moves forward, dividing the tissue presented to it by the closing blades. Meanwhile the tissue is held steady by the squeezing action of the blades (symbolized by barbs in the drawing)

Note: The edges of the blades are actually blunt[42]

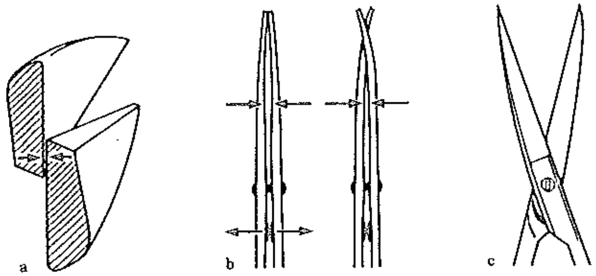


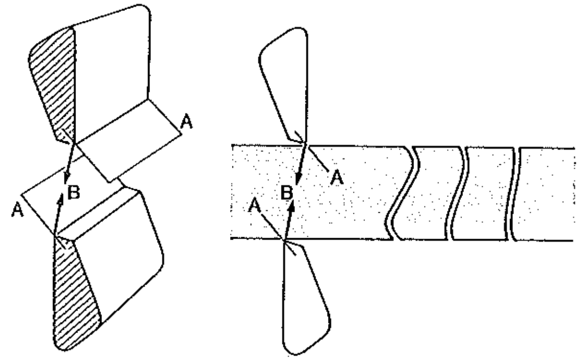
Fig. 2.78. **Analysis of production of shearing stress**

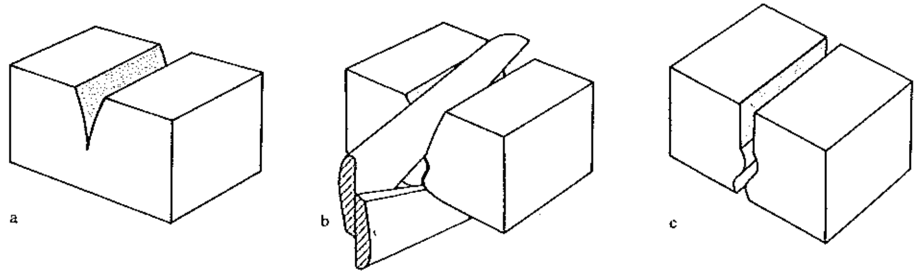
a The stress keeps the edges of the blades pressed together.

b Spring tension is created by the camber of the blades. The side view clearly shows that the blades meet only at a single point. A block (*red*) on the opposite side of the joint helps to maintain the shearing stress. *Left*: Scissors closed; *right*: Scissors half-open.

c Open scissors showing the position of the block (*red*)

Fig. 2.79. **Profile of a scissors cut.** Both the cutting point and the cutting properties of the blades are important in thick tissue layers. In all scissors, an angle exists between the guidance direction *B* and the preferential path of the edge *A*.[46] This results in an S-shaped cut whose curvature depends on the resistance, mobility, and thickness of the tissue. *Note*: The obliquity of the guidance path *B* results from the camber of the blades





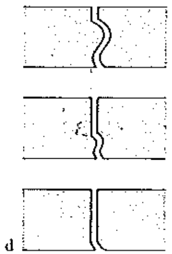


Fig. 2.80. **Preliminary thinning of tissue layers**

a Preliminary cutting with a knife yields a straight cut profile.

b If the preliminary cut is completed with a scissors, the new cut profile is not straight like the knife cut but is curved in accordance with the cutting properties of scissors.

c The result is always a "step" in the incision.

d The size and shape of the step depend on the thickness of the tissue layer left by the preliminary cut. Three examples show the results with superficial (*top*), medium (*center*), and deep (*bottom*) preliminary cuts

Cutting by Closing the Blades

In this, the basic mechanism of scissor cuts, the tissue is divided by a **cutting point** (Fig. 2.77). The *preferential path* then is a line that can assume arbitrary shapes.[43] Scissors are extremely versatile, therefore. However, they cut with a cutting point only in very thin ("two-dimensional") tissue layers such as conjunctiva, lens capsule, iris, and cornea thinned by partial-thickness incision. In thick tissue layers such as full-thickness cornea and sclera, there is a phase, prior to formation of the cutting point during closure, in which the properties of the two individual cutting edges predominate. The preferential paths of the cutting edges are not lines but planes which cut in a direction different from that of the cutting point.

The *cutting point* is formed by the two blade edges pressing against each other during closure (Fig. 2.78). One vector component of the pressing force is created by the shearing stress associated with the scissors construction, the other by the closing action itself. The *shearing stress* is created by the camber of the blades and is reinforced by a block on the opposite side of the joint.[44] This stress largely determines the cutting ability of the scissors, since a cutting point exists only if the force pressing the edges together is greater than the tissue resistance pushing them apart.[45]

The **profile of the scissors cut** results from the *movement of the cutting edges* against the cutting point and the *concomitant tissue movements* induced by the action of the instrument. The blade edges themselves are blunt. They exert a cutting action only if they crush the tissue sufficiently to increase its sectility. Because the guidance path of the scissors does not coincide with the preferential path of the edges, the profile of a scissors cut in thick tissue is *S-shaped* (Fig. 2.79). The thicker the tissue layer to be divided, the more pronounced this curvature (Fig. 2.80). The cut profile is also affected by the "sharpness" of the cutting process and by the mobility of the tissue layers. Both factors change as closure proceeds. At the start of the cut, when the blade angle is large, they are not the same as at the conclusion when the blade angle is small. The cut profile changes accordingly.

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[42] The finish of the blade edges serves mainly to ensure a smooth working action. Some roughness is acceptable since the friction will prevent tissue slippage and thereby enhance "sharpness" (principle of serrated hairdressing scissors).

[43] Thus, scissors function neither by the "bite" mechanism where two linear cutting edges simultaneously appose for their full length nor by the "punch" mechanism where a linear cutting edge is pressed against a base.

[44] In scissors that do not have this block, tension must be maintained by manual pressure. Such scissors are usually designed for right-handed use; left-handed operators require special models.

[45] Thus, the cutting ability of the scissors cannot be judged by visual inspection of the blade edges. This can only be tested by function, i.e., making trial cuts in a tissue-like material (such as a soft, moist paper towel).

[46] Remember: The preferential path of the single blade is the bisector of the ground edges.

Fig. 2.81. **Analysis of scissors closure**

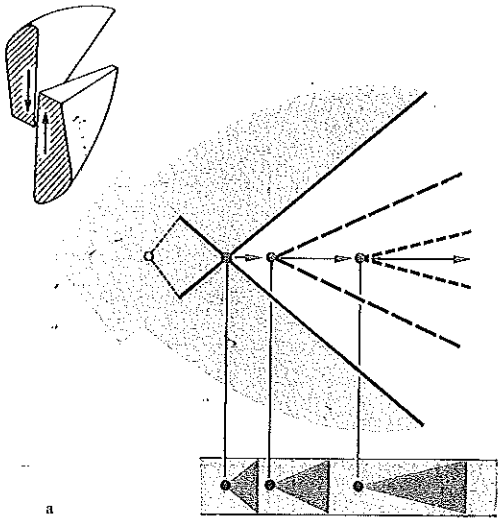
a Closure of the scissors produces the second vector component needed to form the cutting point (*top*). As this point moves forward (*center*), the aperture angle between the blades, and thus the angle of attack at the tissue, is progressively reduced (*bottom*).

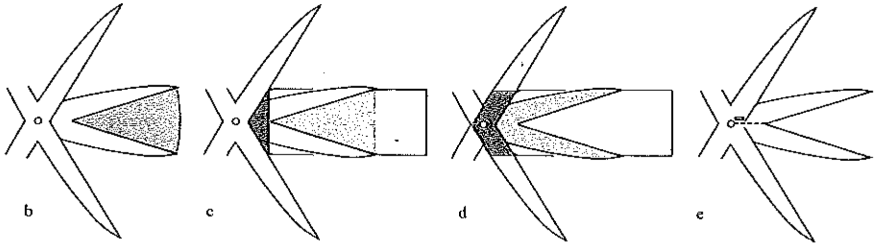
b As closure proceeds the interblade area (*red*) diminishes, and the danger of inadvertent tissue lesions is reduced.

c The amount of tissue lying between the blades (*gray*) increases, and with it the resistance to closure. The tissue tends to shift ahead of the cutting point.

d The immersed blade area (*gray*) increases, and there is a proportional increase in lateral resistance. Lateral deviations of the blades become more difficult.

e The lever arm between the joint and cutting point (*solid red line*) lengthens (*broken red line*), while the lever on the other side of the joint (the handle side) remains constant. As a result, progressively less force is transmitted by the fingers





The **longitudinal scissors cut** is produced by *forward motion of the cutting point*. When the blades are held at a fixed angle, this advancing motion can be produced simply by *pushing* the scissors forward; the shape of the cut then conforms precisely to the *guidance motion* of the operator. This can be successfully done only with a low, uniform tissue resistance.

When tissue resistance is high, the cutting point must be advanced by *closure* of the scissors (the *working motion*) (Fig. 2.81 a). The cutting point moves forward along the blade edges, producing a cut whose shape conforms to the *curvature of the blades*.

During closure of the scissors, the aperture angle of the blades decreases while the amount of tissue between the blades increases. As this occurs, the tissue offers mounting resistance to blade closure, and there is increasing *resistance to the advance of the cutting point* (Fig. 2.81 c).[47] The *lateral resistance* also rises, making it more difficult to change the direction of the cut (Fig. 2.81 d). Meanwhile, the force transmitted to the cutting point diminishes (Fig. 2.81 e). Consequently the sharpness and versatility of the scissors decline steadily as closure proceeds.

If the proposed **shape of the cut** is to *conform* to the shape of the blades, the cut can be performed in one maneuver by a simple closing movement of the scissors. The rising lateral resistance is advantageous for it helps to keep the scissors on the intended path.

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[47] This working resistance is directed against the advance of the cutting point and against the squeezing action of the blades, i.e., against movements with forward-directed vector components. It causes the tissue to shift toward the blade tip, and the final cut is shorter than planned. So with a high resistance, the scissors must be forcibly thrust forward to press the tissue against the cutting point and avoid undesired shortening of the cut.

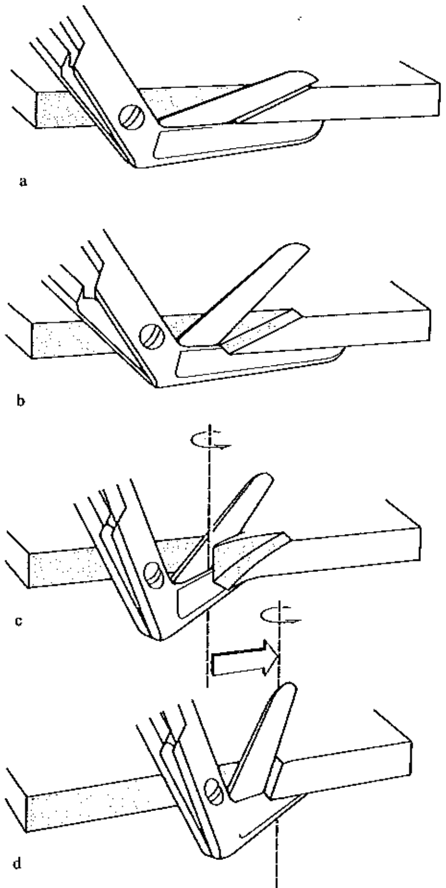
Fig. 2.82. **Reapplying the scissors when cutting in steps**

a Incomplete closure of the blades leaves a partially divided wedge of tissue.

b When the blades are reapplied, their aperture angle is larger than the angle of the tissue wedge.

c If the guidance direction is changed when the scissors is reapplied (*narrow arrow*), the partially divided tissue wedge creates a serration.

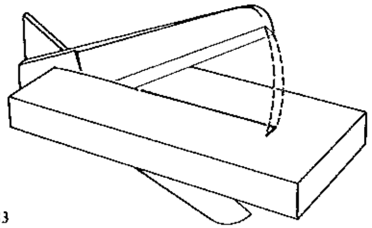
d This is avoided by first continuing the cut in the original direction (*wide arrow*) after reapplying the scissors, and not turning the scissors in the new direction until the tissue wedge is completely divided



2.82

But if the shape of the cut is to *deviate* from the shape of the blades, it is necessary to combine the closing motion with one or more guidance motions. Here it is advantageous to maintain a large blade aperture, for this reduces lateral resistance and makes it easier to change the direction of the cut. A large aperture angle is maintained by only partially closing the scissors and then reapplying it to the tissue with the blades widely opened. However, with each reapplication of the scissors and thus with each abrupt *change in the aperture angle*, there is an associated change in resistance and tissue mobility. The result is an abrupt change in the profile of the cut. This *serration effect* relates to the working motion of the instrument and is unavoidable when the cut is performed in multiple steps. Another type of serration is based on guidance motions, and this type can be avoided by carefully following the original direction of the cut when the blades are reapplied to the tissue (Fig. 2.82) and by avoiding complete closure of the blades (Fig. 2.83).

Fig. 2.83. **Serration effect on complete closure of the scissors.** If the scissors tip penetrates completely into the tissue, its leading edge acts as a cutting edge and produces a small lateral cut



2.83

In summary, the *advantages* of the scissors cut are *versatility*, or the ability to make cuts of arbitrary shape, and the effective *sharpness* provided by the crushing action of the blades, which keeps tissues from shifting away from the cutting point. Another advantage is *safety*, since the instrument will divide only tissue lying between the blades. This eliminates the risk of inadvertent lesions outside the interblade area (Fig. 2.81b); the safety margin can be increased by cutting with a small blade aperture.[48]

The *disadvantages* of the scissors cut correlate with the thickness of the tissue to be divided. Consequently they can be reduced by making a preliminary, partial-thickness incision in thick tissue layers. The thinner the remaining layer, the lower the resistance, and the more regular the profile of the finished cut (Fig. 2.80d). A thinned tissue layer actually maximizes the advantages noted above.

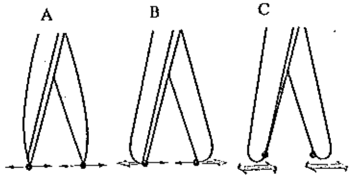
Cutting by Opening the Blades

In this technique the scissors cut with the *back of the blades*. This converts the scissors to a *blunt instrument* suitable for the **splitting** (blunt dissection) of preexisting tissue spaces. Their advantage over simple wedge-shaped instruments is that each blade utilizes the resistance produced in the tissue by the opposing blade, so this technique can open spaces that are crossed by extremely distensible fibers.[49] Although the shape of the resulting "cut" depends chiefly on the path of least tissue resistance, it is prudent to adapt the guidance path of the blades (by the choice of blade shape and position) to the intended shape of the cut to avoid unintentional trauma to surrounding tissues.[50]

Cutting with the Blade Tips

Cutting with the blade tips may just involve the **final phase of cutting by scissors closure**, in which tissue is sectioned by the cutting point. If the outermost ends of the blades are to be used, a scissors is required whose ground edges extend all the way to the tips (i.e., sharp or semirounded scissors, Fig. 2.84A, B). But cutting with the blade tips in a strict sense means using them as **instruments in their own right**. They can be *thrust forward* into tissue as a prelude to cutting by opening or closing the blades: Sharp points can force their way through the tissue in the guidance direction,[51] while blunt tips behave as spatulas and will not damage surrounding structures when the blades are introduced into cavities or spaces.[52] When moved in the *lateral direction* (movement effected by opening or closing the blades), the tips behave as blunt or sharp instruments depending on their shape and position. *Sharp tips* act as point cutting edges regardless of their direction of motion (Fig. 2.84A). They produce linear incisions and differ from free point cutting edges only in that their path is limited by the construction of the scissors. *Rounded tips* are blunt in any direction (Fig. 2.84C). The cutting ability of *semirounded tips* depends on the leading edge: The tip is blunt during opening but sharp during closure (Fig. 2.84B). In addition, the effective sharpness during cutting with the blade tips depends on the *position* in which they are held: While sharp points will cut tissue with the scissors held in any position, thicker-bladed scissors must be applied perpendicular to the tissue surface (Fig. 2.85).

Fig. 2.84. Shapes of scissors tips



Shape of blade tips	sharp	semirounded	rounded
Ground edge extends to extremity of blade?	yes	yes	no
Action of blade tips when *thrust* into tissue			
– with blades open (preparatory to cutting by closure of scissors)	sharp	mostly sharp	blunt
– with blades closed (preparatory to cutting by opening the scissors)	sharp	blunt	blunt
Cutting actions of tips during *working motion*:			
– closure of scissors	sharp	sharp	blunt
– opening of scissors	sharp	blunt	blunt

Red dots: Ends of the ground edge; *thin arrows*: "Sharp" movements of the tips; *thick arrows*: Blunt movements.

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[48] Example: Trimming suture ends after tying. Cutting with the scissors almost closed (i.e., cutting close to the tip) reduces the risk of damage to tissues or other threads.

[49] Example: Separation of episcleral fibers in operations for strabismus or retinal detachment (see Fig. 4.11); separation of epiretinal membranes in vitrectomies.

[50] Example: In enucleations, lesions of orbital tissue are avoided by using curved blades and holding the scissors snugly against the globe when opening them.

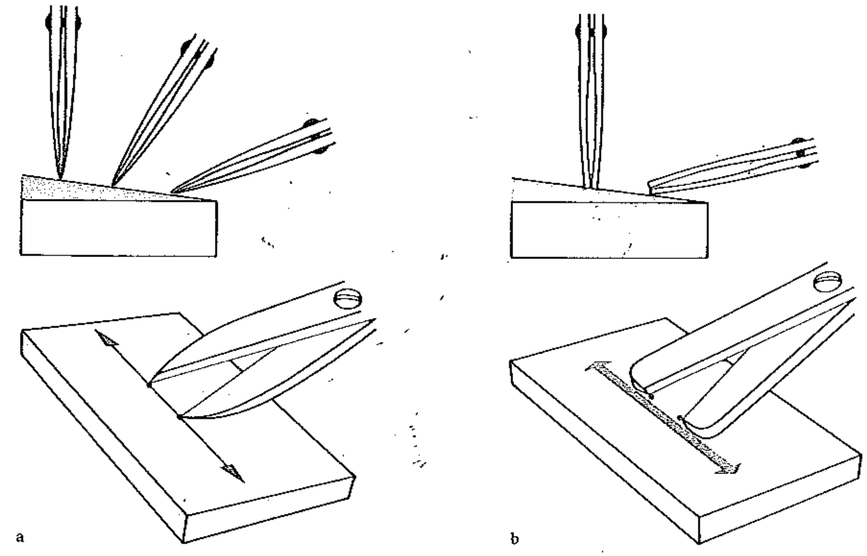
[51] Examples: "Pointed" scissors for penetrating the lens capsule; piercing the iris for iridotomies.

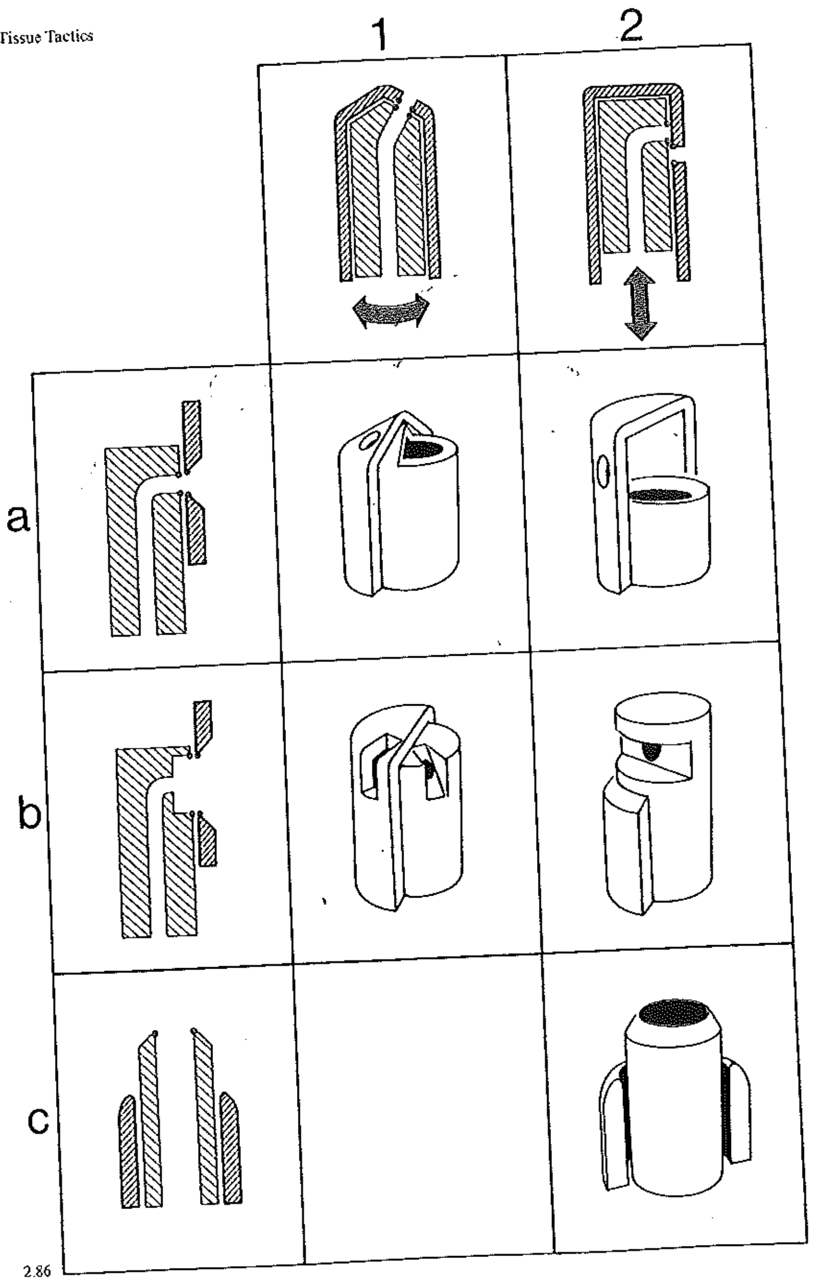
[52] Examples: Muscle scissors for advancing along the globe surface in the episcleral space; corneal scissors for introduction into the anterior chamber (see Fig. 5.53).

Fig. 2.85. **Cutting with the blade tips**

a When a sharp-pointed scissors is used to cut fibers (*gray*) on hard underlying tissue (*white*) (e.g., episcleral fibers on the sclera), the cutting edge can meet the tissue fibers at any angle and can make a sharp cut in any position (*thin arrow*).

b With nonpointed tips, the cutting point (*red*) stands away from the fibers by the thickness of the blade, and the tips behave as blunt instruments (*thick arrow*). The cutting point can act on the fibers directly only if the blades are applied perpendicular to the tissue surface (see Fig. 4.13)





2.86

Fig. 2.86. **Suction cutting instruments**
Column 1: Instruments with a rotary cutting action (continuous or oscillating).
Column 2: Instruments with a reciprocating (axial) cutting action.
Row a: Instruments in which the resection port and aspiration port are the same ("sipping" action).
Row b: Instruments in which the resection port is separated from the aspiration port by an antechamber ("nibbling" action).
Row c: High-frequency vibrators (emulsifiers).
Red: Cutting edges

Suction Cutters

Suction cutters are miniaturized instruments that combine the functions of grasping, cutting, and transport in a very small volume (Fig. 2.86). The working end of the instrument contains an *aspiration port*, a *resection port*, and a *transport channel*. If space permits, fluid inflow can be provided through a coaxial sleeve (suction infusion cutter).

These miniaturized instruments are not easy to monitor because there is no tactile feedback from the cutting action; visual feedback must be based on the observation of the effects in the tissue[53] and this means that it will be too late to react in case indesired effects occur.

Consequently, one must **anticipate the results** and predict them based on the knowledge of the functional characteristics of the instruments. In order to determine the requirements as to instrument design and handling, one should define whether the goal of a given action is **cutting or traction.**

Cutting Ability and Sectility

The cutting action occurs at the **resection port,** where the tissue is presented to the cutting edge. The resection port may or may not be identical with the **aspiration port,** that is, the narrowest site in the aspiration system which may be occluded by aspirated tissue.

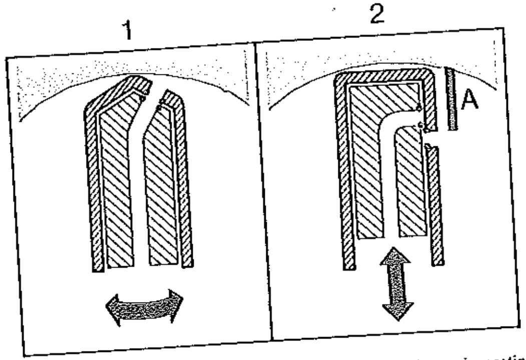


Fig. 2.87. **Position of the inlet in suction cutters**
Left: In rotary-action cutters, the inlet can be located close to the tip. This makes it possible to cut close to tissue surfaces lying *ahead of* the tip.
Right: Cutters with a reciprocating action have a side opening placed some distance back from the tip. The minimum distance *A* depends on the amplitude of the cutting motion

For *cutting* the tissue is divided by a **punch mechanism** which requires that the cutting edges meet for their full length under uniform pressure.[54]

Only motions accross the resection port are effective for cutting. Blade excursions beyond the aperture may merely cause side-effects because in case of insufficient sharpness the blade pulls undivided fibers that transmit traction to surrounding tissue. The length of blade excursions, therefore, is critical in instrument design: *Rotary* actions have an infinitely long travel and consequently pose high risks. By contrast, the amplitudes of an *oscillating* or "chopping" action – whether about the central axis (Fig. 2.87-1) or along the axis (Fig. 2.87-2) – can be kept at a minimum.

For *immobilisation* of the tissue in front of the cutting edge either aspiration by occlusion, enclosure, or inertia can be used. **Aspiration by occlusion** is suitable if the substrate is sufficiently compliant (Fig. 2.88).[55] Here the aspiration can serve further to increase the sharpness of the cutting action: In instruments whose cutting edge passes directly over the aspiration port, so that the aspiration port and the resection port are identical (Fig. 2.88a), the suction makes the tissue tense as it is presented to the cutting edge and thus improves its sectility.

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[53] Due to the short and rapid travel the movements of the blade are invisible.

[54] This mechanism is entirely different from the scissors mechanism in which the blades meet at a single point and, by their relative movements, drive the cutting point forward (see Fig. 2.77). Full edge-to-edge contact requires precision engineering. Instruments whose resection port is *at the front of the tip* pose the fewest technical problems (Fig. 2.86-1) since the cutting edge can be pressed forward against the opposing edge by a spring mechanism. Any frictional wear is advantageous as it improves the pressure and contact between the edges. In *side-cutting* instruments (Fig. 2.86-2) it is more difficult to press the cutting edges together by active force, and wear degrades the contact between the edges over time.

[55] Note: In this technique the aspiration port is occluded by the material to be aspirated, so there is no danger of inadvertent aspiration of neighboring tissue.

Immobilisation by enclosure is used for tissue that will not occlude the aspiration port because of its firm consistency. For this purpose, instruments are used in which the aspiration port and the resection port are separated by an *antechamber* (Fig. 2.86b). The geometry of the antechamber is such that material introduced into the chamber cannot evade the cutting edge (Fig. 2.89). Here, suction does not contribute to grasping the tissue.[56] Also suction does not increase tissue tension. The only way then to improve the sharpness of the cutting process is to increase the speed of the cutting motion. *Note*: The critical factor is the speed of the individual stroke, which does not necessarily correlate with the cutting frequency.[57]

Immobilisation by inertia: The principle of high-speed cutting finds its extreme application in *ultrasonic vibrators*. These instruments operate at such high speed that the tissue is held in place for cutting purely by its own *inertia*. The effective "sharpness" of the cutter depends critically on speed, so much so that the characteristics of the cutting edge are of minor importance. There is not even a need for an opposing edge, so the ultrasonic vibrator may consist of a simple open tube.

The appropriate *excursion* of the vibrator tip depends on the mass of the tissue to be resected. If the excursion is too small, the cutting action is poor. If too large, only a portion of the applied energy goes into dividing the tissue; another portion produces concomitant movements of the particle, which may even be transmitted to the environment. Therefore, as the tissue mass is debulked during the procedure, the tip excursions should be reduced accordingly so that the tissue continues to be divided rather than shaken.

Because part of the applied energy is converted to heat, continuous **cooling irrigation** should be maintained to avoid damage to surrounding tissues. This complicates volume regulation and makes the chamber more susceptible to the effects of external forces (see Fig. 1.5c and 1.7).

The Control of Cutting and Traction

Whether cutting or traction shall predominate in the instruments action depends on the relation between *frequency* and *suction*.

For a given level of suction, the frequency of the cutting motion determines the tissue volume that is resected per operating cycle. **Changes in the cutting frequency,** therefore, may require a **modification of the suction.** If the suction is too **high** relative to the cutting frequency, too much tissue is drawn into the tip before it is divided, and the instrument mainly exerts traction on surrounding structures. If the suction is too low relative to the cutting frequency, there will be insufficient time to present enough tissue to the cutting edge, and the instrument will have no effect. Therefore, the **rules for regulating the cutting frequency** at a given force of suction are: If the goal is to *avoid* any traction on tissues,[58] the cutting frequency should be high initially and gradually reduced until a visible cutting action is obtained. But if the tactical goal is traction,[59] one should start with a low frequency, observe the effect, and begin cutting only when it is appropriate to discontinue the traction.[60]

The main danger in the use of suction cutters is unplanned traction because this may act on surrounding tissue and cause damage at unexpected sites. The *general safety strategy*, then, aims at preventing unplanned traction altogether and minimizing the consequences in case it should occur in spite of all precautions. This means:

- instrument **design** with short travel of blade
- instrument **setting** with high cutting frequency at the beginning and decreasing gradually depending on the requirements of a specific situation
- instrument **position** at sufficient distance from critical areas because side-effects will be noted only after they have occurred.

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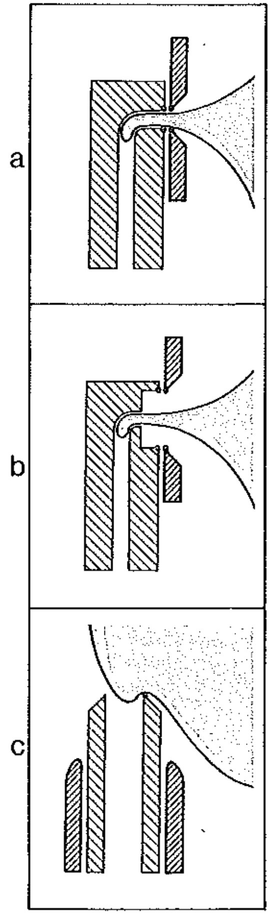
[56] This applies to "nonoccluding" material. Compliant tissue will be sucked into the tip despite the presence of an antechamber. Here aspiration serves mainly to deform the tissue so that it will fit through the antechamber.

[57] Even with a low frequency, the individual stroke may be very fast.

[58] E.g., in a vitrectomy.

[59] E.g., for the removal of cataractous lens matter.

[60] The problems related to ultrasonic vibrators will be described in chapter 8.3.3.



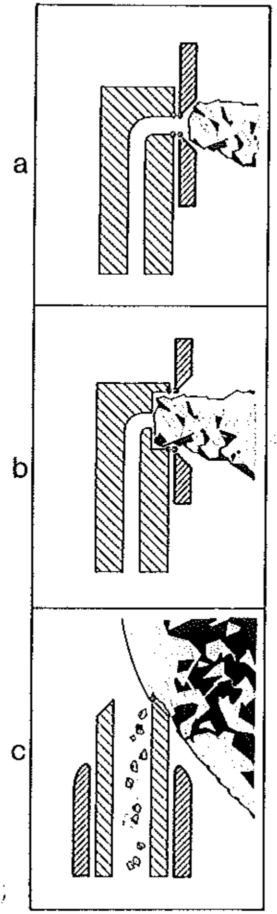
2.88

Fig. 2.88. **Grasping of pliable material**

a Aspiration by occlusion: Tissue fibers are drawn into the aspiration port and are simultaneously made tense for sectioning by the cutting edge. Sectility, then, can be improved by increasing the suction.

b In cutters with an antechamber, the site where the tissue is grasped (aspiration by occlusion at the narrowest diameter) is separated from the cutting edge. As a result, tissue tension at the aspiration port does not provide effective tension at the resection port, and sectility is not enhanced by increasing the suction.

c Ultrasonic vibrators are ineffective on material having a high compliance and low mass, because the vibrating tip will push the tissue aside rather than cut it



2.89

Fig. 2.89. **Grasping of rigid material**

a Aspiration by occlusion is ineffective for grasping rigid material, for the latter cannot conform to the aspiration opening. Thus, the instrument cannot cut material whose cross-section is greater than that of the aspiration port.

b Instruments with an antechamber can cut tissue that fits into the chamber. *Note*: Suction does not improve the grasping effect. It only increases the risk of inadvertent aspiration of surrounding tissue because the suction port is not occluded.

c High-frequency vibrators are effective cutting instruments on firm material whose inertia keeps it from being pushed aside

Needles

Needles consist of a cutting component (*head*) which forms the suture track, a handle (*shaft*) by which the needle is held, and an *eye* through which the suture material is passed (Fig. 2.90).

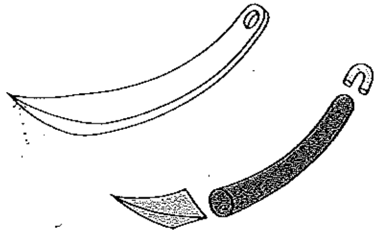


Fig. 2.90. **The parts of a needle.** A surgical needle consists of a head (pointed tip and lateral cutting edges), shaft, and eye

The **cross-section of the needle track** depends on the *arrangement of the cutting edges*, each of which cuts its own path through the tissue (Fig. 2.91). Thus, a *three-edge* head makes three cuts, each in the direction of the corresponding preferential path. A *two-edge* head makes two cuts on the same plane. A *round-bodied* (edgeless) needle tears a channel through the tissue. Needles whose heads have a larger cross-section than the parts that follow produce a large-diameter track and decrease the resistance to passage of the shaft and thread.

The **longitudinal profile of the needle track** corresponds to the *path of the needle tip*. Being a geometric point, the needle tip can in theory be guided in any direction. But in practice its mobility is limited by lateral resistance, which varies with the configuration of the preferential paths of the lateral edges (Fig. 2.91) and with the shape of the shaft.

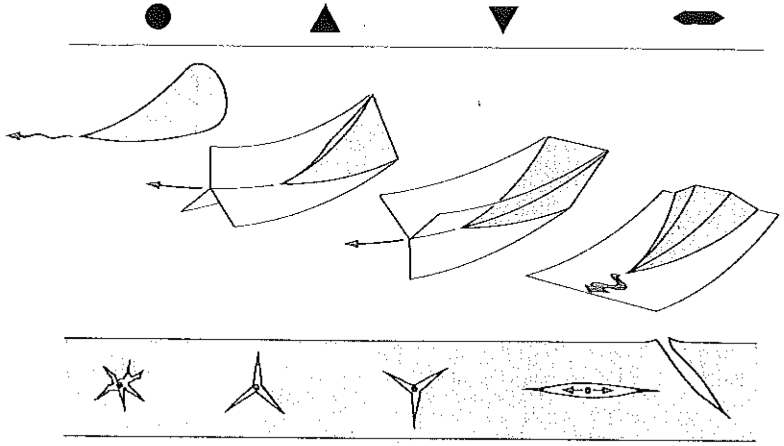


Fig. 2.91. **Shapes of needle heads.** The arrangement of the lateral cutting edges and their preferential paths determine the cross-sectional shape of the needle track.

Top row: Cross-section of needle head.
Middle row: Three-dimensional drawing of head with the preferential paths (red outline).
Bottom row: Cross-section of resulting needle tracks. Red dot corresponds to the position of tip and thus to the surgeon's intent.

Round heads (*left*) penetrate tissue by blunt dissection. The cross-section of the track follows tissue interspaces of least resistance.
Heads with three cutting edges (*center*) have three lateral preferential paths and cut a track with a Y-shaped cross-section. The cross-section of the track may extend upward (*center left*) or downward from the center of the Y (*center right*) depending on the position of the vertical edge. The three-dimensional arrangement of the preferential paths creates lateral resistances that stabilize needle guidance.

Heads with two cutting edges (*right*) form a slitlike track whose central axis corresponds to the path of the needle point. The preferential paths of the two cutting edges are congruent, so there is relatively little resistance to lateral deviations. This type of needle head can easily lacerate the tissue (*right*) unless it is guided strictly parallel to the tissue surface (*left*)

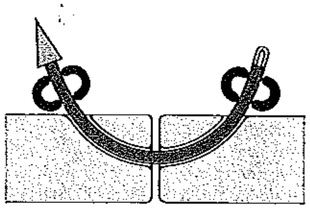


Fig. 2.92. **Length of the shaft.** To preserve the delicate head and eye, the needle is gripped *only* by its shaft or "handle." The shaft must be long enough to be grasped by the needleholder (*black*) during insertion and emergence of the needle

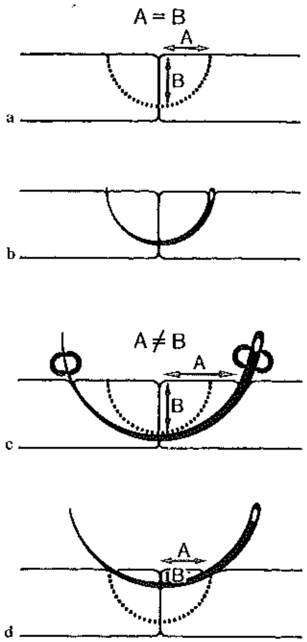


Fig. 2.93. **Problem of incongruity between the needle shape and proposed suture tract**

a The proposed suture tract is semicircular, i.e., the distance from the wound edge (*A*) equals the suture depth (*B*).

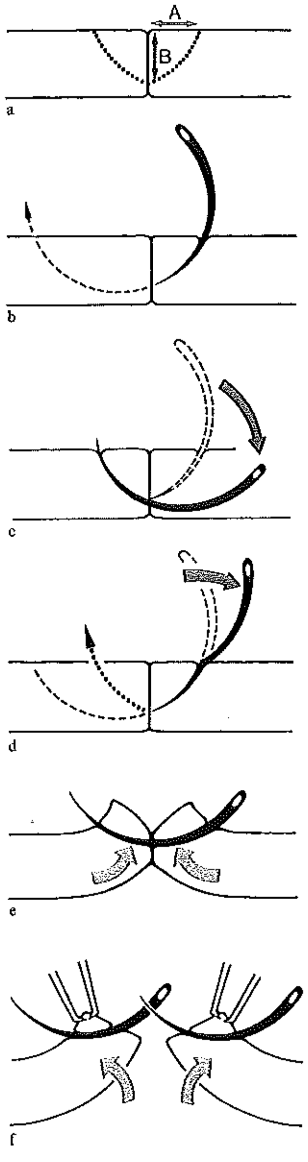
b A needle perfectly congruent to the planned suture tract cannot be inserted completely nor withdrawn with a needleholder.

c A needle can be grasped only if it is longer than the tract. But then the radius of curvature is also increased. If this needle is inserted to the planned depth (*B*), the bites will be longer than intended (*A*).

d If the same needle is inserted and withdrawn at the planned distances from the wound margin (*A*), the track will be more superficial than intended (*B*)

Lateral resistance is lowest when the path of the needle tip precisely follows the curvature of the shaft, i.e., when the needle shape is perfectly congruent with the planned suture track (Fig. 2.93a, b). In practice, the shaft must be somewhat longer than the suture track so that it can be easily grasped by the needleholder during suturing (Fig. 2.92). The effect of this incongruity is increased lateral resistance when the shaft is passed through the tissue, causing deformation of the tissue or the needle (Fig. 2.94). This places correspondingly high demands on needle stability: the greater the incongruity between the needle and the suture track, the higher the tissue resistance, and the more stable the needle must be. Conversely, the finer the needle, the more closely its shape should conform to the planned suture track (Fig. 2.95).

The optimum shape of the eye depends on the thickness of the suture material (Fig. 2.96), since the addition of the thread diameter should not significantly increase the total cross-section. The extremely fine threads used in microsurgery pose no problem in this regard, so the advantage of "atraumatic" sutures lies more in their convenience (no threading) than in a true technical superiority.



2.94

Fig. 2.94. **Solving the incongruity problem**

a The proposed semicircular track is most closely approximated by two segments of flatter curvature that are made by inserting and withdrawing a longer needle at the planned entrance and exit sites in each wound lip.

b If the needle were allowed to follow its preferential path after insertion in the first wound lip it would emerge too far from the wound line at the second wound lip.

c This is avoided by tipping the needle backward before passing it up through the second wound margin.

d If the needle is not strong enough, it will bend when this maneuver is attempted.

e If the needle can overcome the tissue resistance, the wound margins will deform instead of the needle.

f As a compromise, the needle can be passed in two steps: It is brought out through the first wound surface and then reinserted into the opposing wound surface. So rigid tissue is not deformed by the needle itself, but is bent manually with a strong grasping forceps. The difficulty in this procedure is to find the proper insertion site in the opposing wound surface

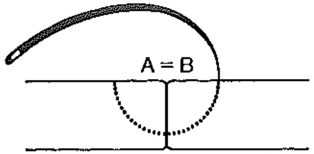


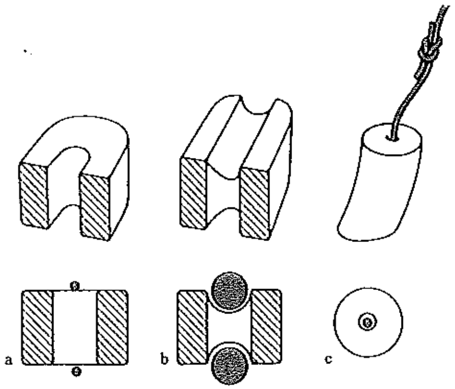
Fig. 2.95. **Compound circle needle.** The tip has a smaller radius than the shaft. Its shape is closer to that of the proposed track, so the deforming forces on the needle and tissue are reduced. Once the track has been cut with the heavily curved tip, the shaft, with its gradually increasing radius of curvature, will slip through. Increasing deformation of the tissue is inevitable at this stage, but it occurs gradually

Fig. 2.96. **The needle eye and thread diameter**

a *Simple eye* is suitable for thin suture material that adds little to the total cross section (*bottom*).

b *Recessed eye* reduces the total cross section when heavy suture material is used.

c In *atraumatic sutures,* the thread is swaged onto the end of an eyeless needle. If the thread is much thinner than the needle, even a knot can pass through the needle track. This makes it possible, in case of suture breakage, to tie a short strand on the atraumatic needle to a new thread



2.96

2.1.4 Uniting of Tissues

Functions of Sutures

The uniting of tissues by biologic processes such as scar formation is comparable to gluing with a slow-setting adhesive. The surgical uniting of an incision strives to maintain apposition of the wound edges until the "glue" has set, i.e., until the scar has attained sufficient strength.[61]

The **fixation** for this purpose must:

- hold the surfaces to be united in their correct position (*apposition*);
- press the surfaces firmly together to minimize the space that must be bridged by scar tissue (*compression*);
- *retain* the united surfaces in their apposed and compressed state, even when external forces (tension, shear) are applied.

When compression is provided by external forces,[62] the only purpose of sutures is to effect **apposition** (Fig. 2.97). Any type of stitch can give satisfactory apposition, provided the length of the stitch equals the length of the intramural suture track plus the overbridging segment. If **compression** must be effected by the suture itself (Fig. 2.98), apposition becomes problematic because compression sutures invariably cause some tissue deformation.

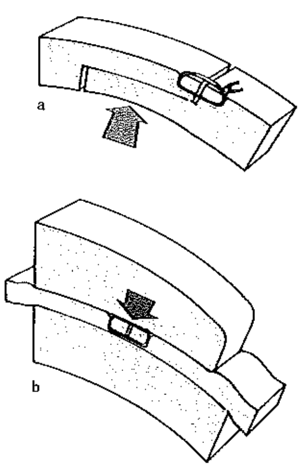


Fig. 2.97. **Apposition sutures.** Simple apposition sutures coapt the wound edges and maintain their position by splinting, but wound compression is effected by endogenous forces (compression zone: *Red*).

a *Intraocular pressure* maintains compression between the surfaces of a stepped incision.

b *Eyelid pressure* presses the conjunctiva against the surface of the sclera

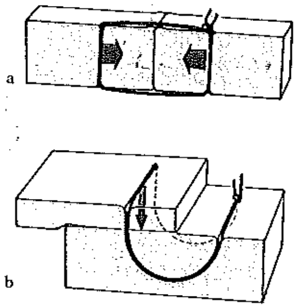


Fig. 2.98. **Compression sutures.** Compression is effected by the suture itself (compression zone: *Red*).

a A *simple interrupted suture* presses the wound margins together.

b A *mattress suture* tacks a thin tissue layer onto a firm substrate

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[61] The requirements of the surgical joining technique are thus determined by the speed of the "setting" process. When a quick-setting tissue adhesive is used, it is sufficient to press the wound margins together briefly with a forceps. If definitive closure relies on scar formation, techniques must be used to retain the apposing "instrument" in the tissue for a sufficient length of time. Long-lasting sutures are particularly useful in poorly healing tissue, i.e., tissue that is poorly perfused due to its anatomy (avascular ocular tissue), surgical trauma (diathermy, excessive suture tension), or the presence of obstructions (foreign matter embedded in the wound, etc.).

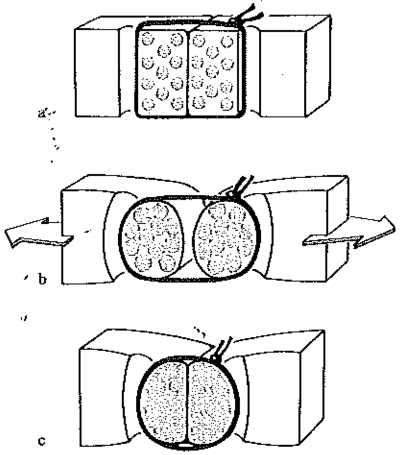
[62] Endogenous forces (e.g., intraocular pressure, lid pressure) or external devices (e.g., contact lenses).

Fig. 2.99. **Mode of action of compression sutures**

a If the suture is exactly the length of the suture tract (and overlying tissue segment), it gives satisfactory apposition.

b Dehiscent traction on the wound margins may then open the wound, since the tissue encircled by the loop is compressible.

c The compression suture is effective when it places sufficient primary compression on the enclosed tissue that the latter can no longer yield to external forces



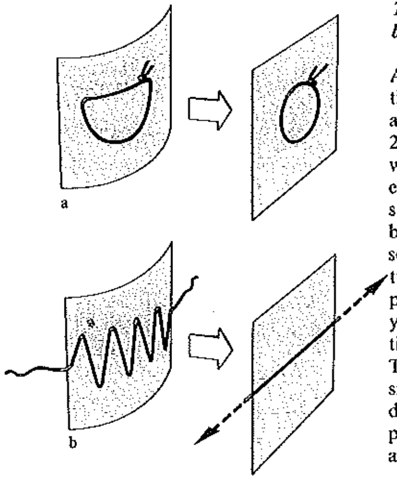


Fig. 2.100. **Rule of suture tightening**

a A simple interrupted suture tends to assume a circular shape when tightened.

b A continuous suture tends toward the shape of a straight line. *Note*: Both forms tend to lie on one plane

Tissue Deformation by Compression Sutures

A suture that causes no deformation of the untouched wound, i.e. a *simple apposition suture* (Fig. 2.99a), cannot effectively maintain wound closure under the action of external forces. The encircled tissue, being compliant, is compressed by the forces, and the wound edges separate (Fig. 2.99b). But if the suture exerts sufficient primary compression, the tissue will no longer yield to external forces, and apposition will be maintained (Fig. 2.99c). The necessary amount of compression ("*adequate compression*") thus depends on the strength of the applied forces that are anticipated in a given clinical situation.

As a suture is tightened to produce compression, the loop of suture material becomes shortened. This alters the original shape of the stitch in a way that can be predicted from the **rule of suture tightening**:

Simple interrupted sutures tend to assume a circular shape when tightened, while continuous sutures tend toward the shape of a straight line (Fig. 2.100).

As the suture becomes deformed, so does the surrounding tissue. Compression sutures always deform the entire wound area in accordance with the type of stitch that is used:

- *simple interrupted sutures* always produce inversion of the wound edges (Fig. 2.101);
- *interrupted mattress sutures* may produce inversion or eversion (Fig. 2.102);
- *continuous sutures* flatten a convex wound area (e.g., the corneal dome), and they straighten out curved incisions (Fig. 2.103). They will deform the surface when the stitches are placed irregularly, i.e at unequal distances from the wound line or at unequal depths (Fig. 2.104).

These types of deformation are a byproduct of suture compression and are unavoidable whenever such compression is required. Where possible, then, it is preferable to effect wound closure without the use of compression sutures. In planned operations it is advantageous to employ incisions that can be ade-

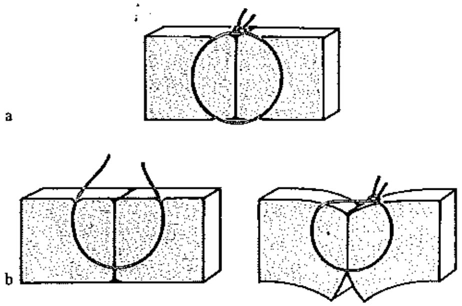


Fig. 2.101. **Tissue deformation by a tightened simple suture**

a The "ideal" suture has a circular shape from the outset and causes very little tissue deformation when tightened.

b Semicircular sutures (*left*) shorten all distances in the enclosed tissue, causing the non-enclosed portion of the wound to gape (*right*)

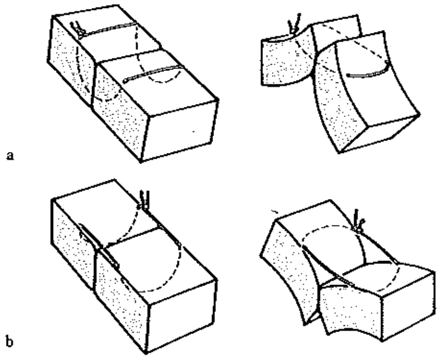


Fig. 2.102. **Tissue deformation by tightened mattress sutures.** Mattress sutures tend toward the shape of a horizontal circle when tightened. Accordingly, the intramural part of the suture is raised while the bridging segment is lowered. This either everts (**a**) or inverts the wound margins (**b**) as all parts of the loop move onto the same circular plane

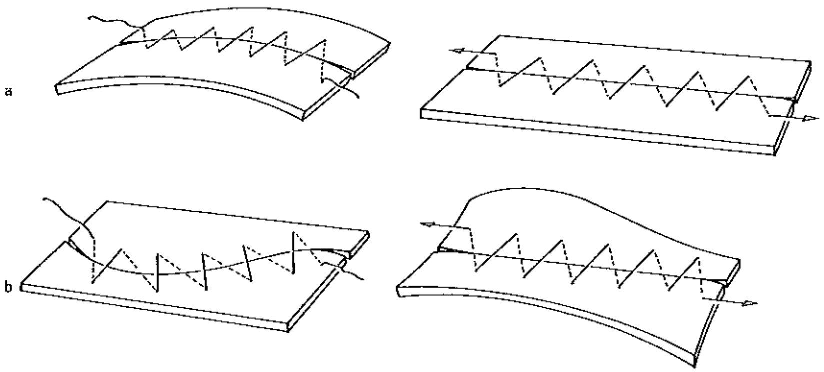


Fig. 2.103. **Tissue deformation by a tightened continuous suture**

Left: Loose suture.
Right: Tight suture.

a Arched tissue surfaces tend to flatten when the suture line is tightened.

b A curved wound line is straightened, accompanied by torsion of the surrounding tissue

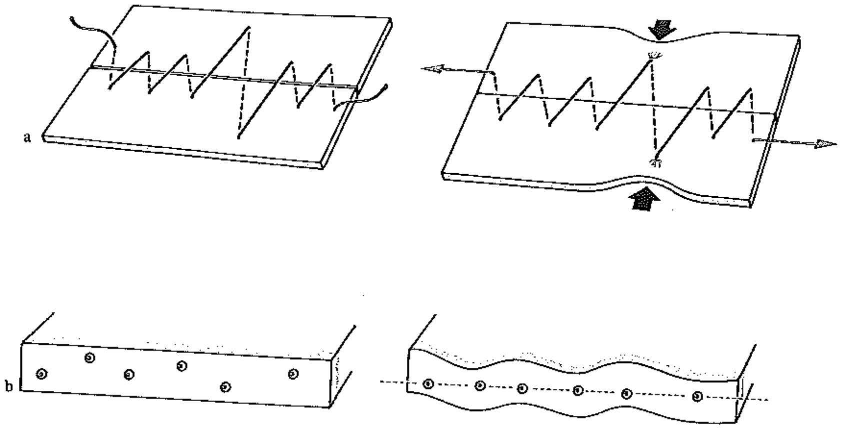


Fig. 2.104. **Tissue deformation by irregularly placed continuous sutures**

a Bites at irregular distances from wound: When the continuous suture tends towards a straight line on tightening, the surrounding tissue is more compressed at the larger bites than at the shorter ones.

b Bites at irregular depths: If the suture tracts occupy different levels on the wound surface, they move onto one plane when the thread is tightened. The surrounding tissue is correspondingly raised or depressed, and the tissue surface becomes irregular

quately closed with simple apposition sutures, i.e., incisions in which other forces can be utilized to compress the wound margins (see Fig. 2.97). In situations where there is no alternative to the use of compression sutures, the optimum stitch is that which will supply the necessary compression with a minimum of side-effects, i.e.,

- a stitch that requires minimal "overcompression" to produce adequate compression along the wound line;
- a stitch whose force vectors produce maximum compressing vector components with a minimum of vectors in other directions.

These concepts will be discussed more fully below.

Force Vectors of Sutures

In technology, compression is effected by means of press or clamp mechanisms that apply the necessary force vectors in an optimum direction (Fig. 2.105a). By contrast, the sutures employed by surgeons always produce *vector components acting in various directions*, some of which do not contribute to wound compression and can actually undermine it (side-effects, see Fig. 2.105b).

The *force vectors* produced by suture tightening can be resolved into three components:

The component that *compresses* the wound margins is directed **perpendicular** *to the* **wound** *surface* (Fig. 2.106). The compressed portion of the wound is the projection of the intramural part of the suture onto the wound surface. If the intramural suture segment is placed *perpendicular* to the wound surface, the compressing vectors are all on the plane of that segment, and the compressed portion of the wound is a *line* – the line where the suture plane intersects the wound surface (Fig. 2.106a). If the intramural segment crosses the wound *obliquely*, its projection onto the wound surface is an *area* (Fig. 2.106b).

The vector component **parallel** *to the wound margin* (Fig. 2.107) tends to *shift* the wound surfaces laterally. It is produced by all sutures that cross the wound obliquely. In *simple interrupted sutures* the shifting vector is incompatible with perfect wound closure, so sutures of this type should not be placed obliquely (Fig. 2.107a, b). In *continuous sutures*, on the other hand, the shifting vectors of the bridging segments can serve to neutralize the shifting vectors of the intramural segments (Fig. 2.107c).

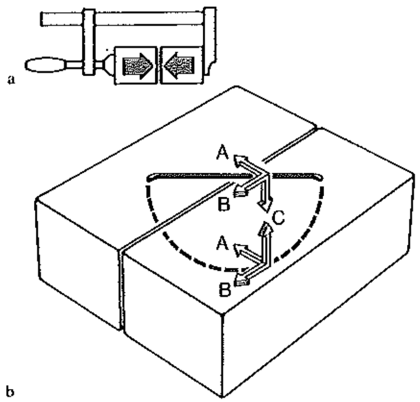


Fig. 2.105. **Force vectors of compressing instruments**

a In technology, compression is effected by tools that produce purely compressive vector components (i.e., perpendicular to the surfaces being compressed).

b Sutures produce three vector components:
A Perpendicular to the wound margin: Compressing vectors.
B Parallel to the wound margin: Shifting vectors.
C Perpendicular to the tissue surface: Inverting or everting vectors

The third vector component is **perpendicular** *to the* **tissue** *surface* (Fig. 2.108). The portion directed upward from the intramural segment tends to *evert* the wound margins, while the portion directed downward from the bridging segment tends to *invert* them. If both segments are on the same plane, as in a *simple interrupted suture*, both components cancel out (Fig. 2.108a). *Continuous sutures*, on the other hand, include successive inverting and everting segments that can produce irregularities in the tissue surface (Fig. 2.108b). This is avoided by placing the loops very close together so that the everting and inverting components are on approximately the same plane (Fig. 2.113).

The effect of these vectors on the tissue is complicated by the fact that the *tissue resistances* opposing the vectors are different in the intramural and bridging segments of the suture. The tensile forces of the *bridging segments* act only at the entry and exit sites of the thread and encounter no tissue resistance. By contrast, the vectors of the *intramural segments* act directly on the tissue, where they are exposed to and limited by tissue resistance. This means that the side-effects of the bridging segments tend to be greater and the desired effects less than in the intramural segments of the suture.

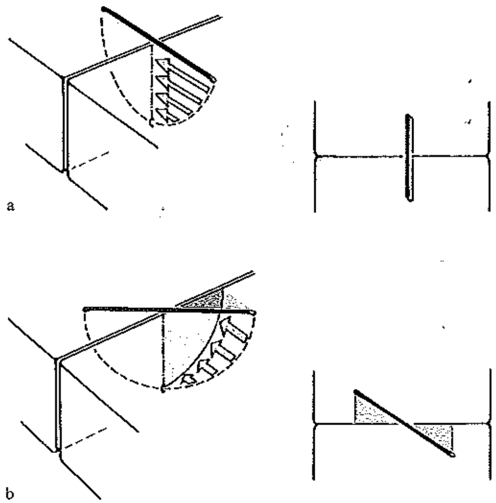


Fig. 2.106. **The vectors of wound compression**

Left: Perspective drawing.

Right: Overhead view of the tissue surface (used in subsequent figures to demonstrate the compressive properties of different stitches).

a With a simple interrupted suture placed perpendicular to the wound line, all the compressing vectors are on one plane. Wound compression occurs on the line where that plane intersects the wound surface. The overhead view (*right*) shows the upward projection of the compressed zone, which is a line.

b With a simple interrupted suture placed oblique to the wound line, the compressing vectors occupy a three-dimensional space between the intramural parts of the suture and the wound surface. The zone of compression at the wound surface is an area. The perspective view (*left*) shows the three-dimensional character of the compression. The overhead view (*right*) shows the compression zone projected onto the tissue surface

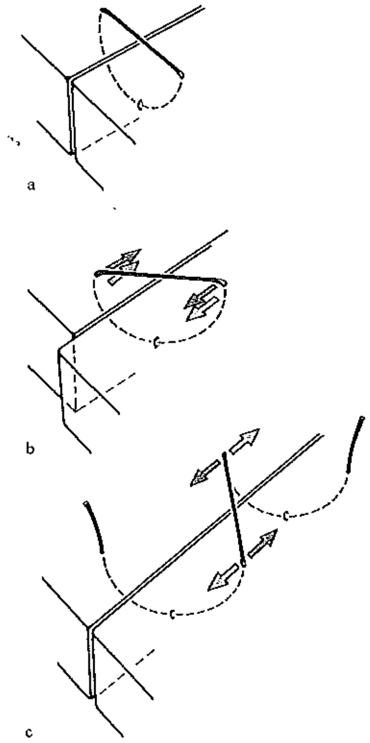


Fig. 2.107. **Vectors of lateral shift**

a Simple interrupted sutures perpendicular to the wound line cause no lateral shift.

b An oblique suture gives rise to shifting vectors. These vectors are equidirectional for the intramural and bridging parts of the suture, so a substantial lateral shift is produced.

c In continuous sutures, the shifting vectors of the intramural and bridging segments are not necessarily equidirectional. They may act in opposite directions and cancel out

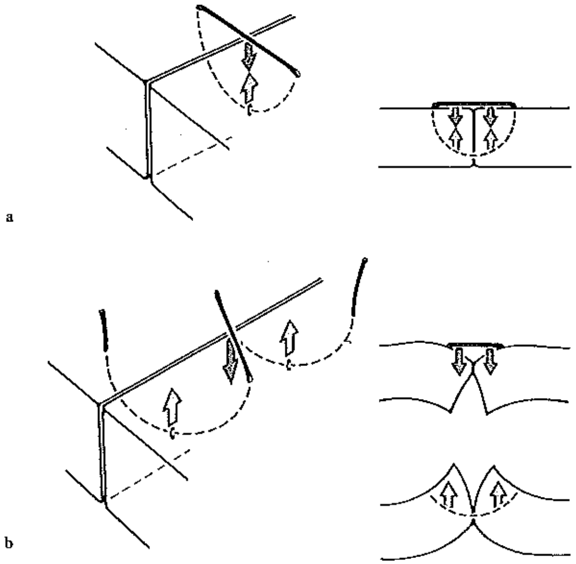
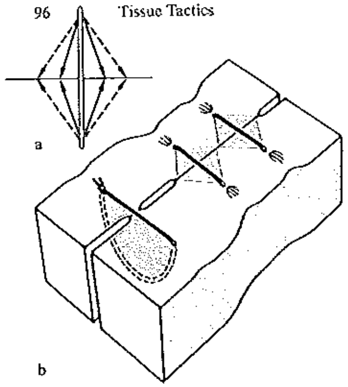


Fig. 2.108. **Vectors perpendicular to the tissue surface**

a In the simple interrupted suture, the perpendicular vectors in the bridging segment (downward directed) and intramural segment (upward directed) are on the same plane, so they cancel out.

b In the continuous suture, the perpendicular everting and inverting vectors are on different planes (*left*). The inverting action of the bridging segment (*upper right*) and the everting action of the intramural segment (*lower right*) deform the tissue level accordingly, producing alternate areas of inversion and eversion along the wound line



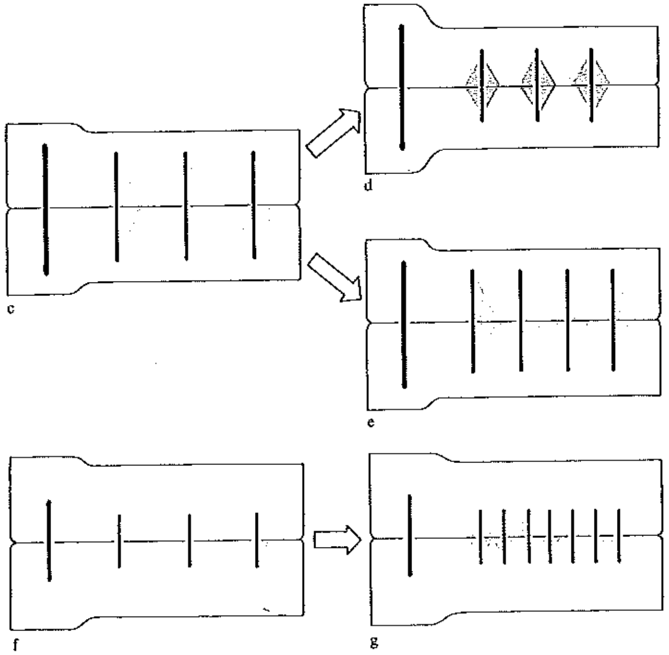


Fig. 2.109. **The effects of simple interrupted sutures**

a Force vectors of simple interrupted sutures. The compressive effect is maximal on the plane between the suture entry and exit sites (the suture plane) and falls off laterally. Thus the action of the suture can be described in terms of "force triangles."

b Wound closure with simple interrupted sutures. If the compression on the suture plane is just adequate (i.e., if the maximum compression is also the adequate compression), compression will be inadequate adjacent to the suture plane (*left*). To ensure wound closure the zones of adequate compression must be contiguous all along the wound (*right*); this requires excessive compression on the suture plane itself.

c–e Wound closure with large sutures.
c Shortening the loop of a simple apposition suture (*left*) widens the compression triangles (*right*). But the zones of adequate compression are not contiguous in the example shown. This is achieved either by shortening the loops further or increasing the number of stitches.

d Shortening the loops further will widen the compression zones but will increase the excessive compression in the suture area.

e Increasing the number of stitches leads to contiguous zones of adequate compression without altering the strength of the compression.

f, g Wound closure with short sutures.
f Shorter loops produce narrower compression triangles than in **c**.

g Consequently the sutures must be spaced closer together than in **e**, resulting in a greater number of stitches

Characteristics of Particular Suture Types

Simple Interrupted Sutures

In simple interrupted sutures, tension is confined to the area of the individual loop of thread. Therefore, simple interrupted sutures are useful for producing a localized tension that is specifically adapted to local conditions.

The side-effects of undesired force vectors are minor in simple interrupted sutures, because the *vertical vectors* cancel out while the *shifting vectors* can be eliminated by a precise suture technique (Fig. 2.106a).[63] The effect of the *compressing vectors* is maximal in the suture plane and diminishes with distance from it (Fig. 2.109a). If the compression on this plane is just adequate, the compression immediately adjacent to the plane will be inadequate. This means that if *adequate compression* is required adjacent to the suture plane, this must be accomplished at the cost of excessive compression (*overcompression*) in the suture plane itself.

Effective wound closure is obtained when the "zones of adequate compression" are contiguous along the entire wound line (Fig. 2.109b).

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[63] If we define "side-effects" as all effects other than compression, we must recognize that in some circumstances these "side" effects can be utilized to achieve specific goals (see Fig. 5.90b).

Thus, the maximum allowable spacing of adjacent interrupted sutures depends on the *width of the zones of adequate compression*. The width of these zones depends in turn on the amount of tissue encompassed and its degree of compression, i.e., on the diameter of the thread loops and the degree of suture tension.

The efficacy of wound closure can be improved by increasing either the number or the width of the compression zones along the wound line. Increasing the number of compression zones means increasing the number of stitches (i.e., narrowing the spacing between them), while widening the compression zones means enlarging the diameter of the thread loops.[64] The relationship that exists between the spacing of the stitches and their diameter leads to the **spacing rule for simple interrupted sutures**: Large suture loops may be spaced at longer intervals than small suture loops (Fig. 2.109e, g).

Continuous Sutures

The loops in a continuous suture line can shift relative to one another as the suture is tightened, leading to a *uniform distribution of tension* over the encompassed area.

Because of the uniform tension, continuous sutures are excellent for situations in which forces act evenly along the wound (e.g., a rise of intraocular pressure). However, they may not protect the wound from locally applied forces (Fig. 2.110). They are appropriate for the closure of straight or circular wound lines (see Fig. 5.95), but they are poorly suited for irregularly shaped wounds that require different amounts of tension at different sites (see Fig. 5.89).

The width of the compression zone depends on the *obliquity* of the intramural segment. Therefore the compression zones can be made contiguous by using the appropriate type of *stitch*. The width of the compression zones can be enlarged simply by *increasing the obliquity* of the intramural segment. This means that continuous sutures can apply adequate compression with minimal overcompression.

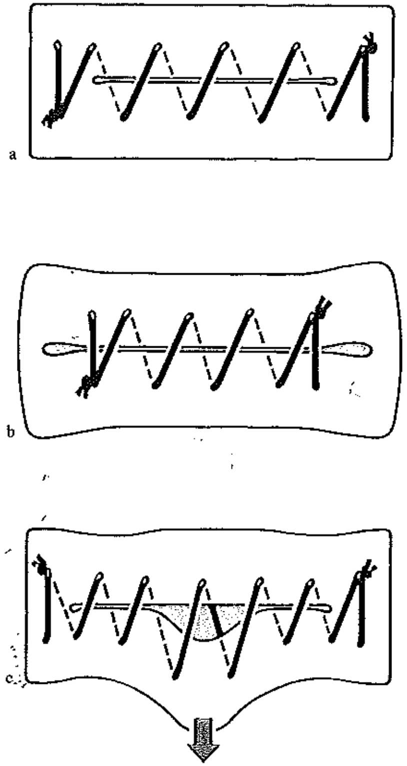

Fig. 2.110. **Mode of action of continuous ► sutures**

a Tension is evenly distributed over the entire suture line, which starts and ends beyond the ends of the wound ("in healthy tissue").

b If the ends of the wound are not encompassed by the suture, they will not be compressed.

c Balanced tension allows localized forces to open one part of the wound while adjacent parts come under increased compression

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[64] In thin tissue layers such as the cornea, such options are limited by the need to make the suture loop as circular as possible (see Fig. 2.101a). Spacing the threads farther apart would cause the stitches to elongate, increasing the risk of significant inversion when the sutures are tightened.

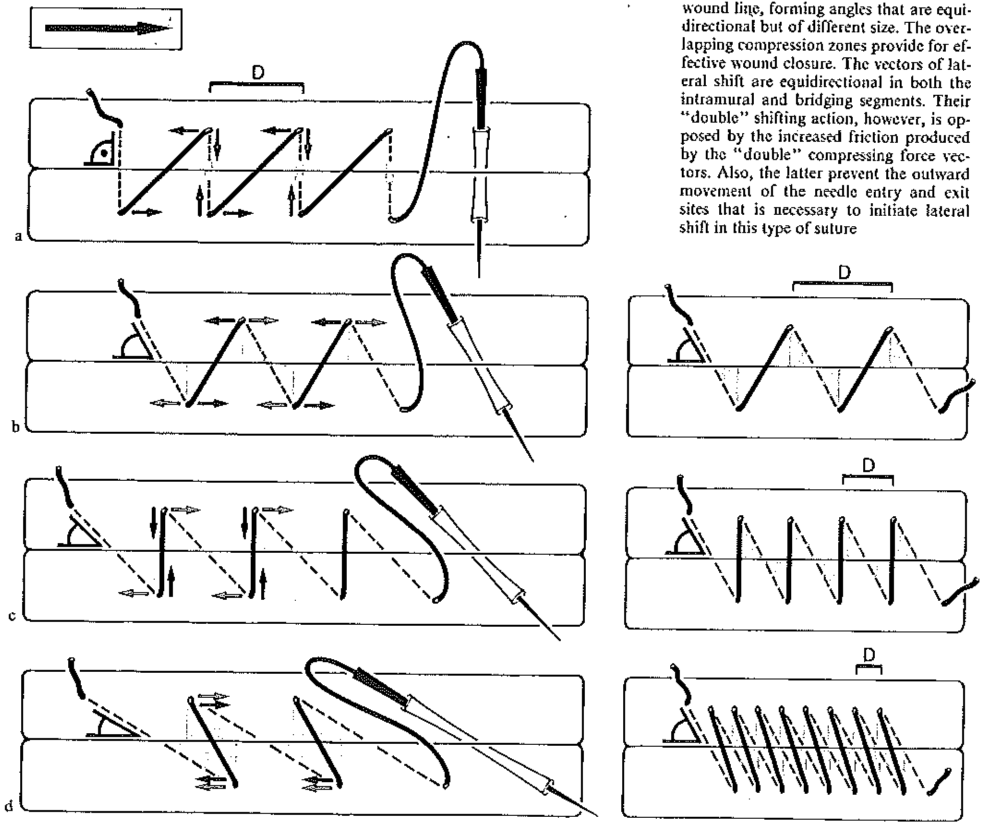
Fig. 2.111. **Compression zones and lateral shift vectors in continuous sutures**
Left: Different stitch patterns are created by changing the angle between the intramural segment and wound line (i.e., by changing the obliquity of needle insertion) while keeping a constant distance (*D*) between the stitches.
Right: Similar patterns are obtained by spacing the stitches differently but keeping the same obliquity.
Pink: Compression zones (cf. Fig. 2.106).
Black arrows: Lateral shift vectors of the bridging suture segments.
Gray arrows: Lateral shift vectors of the intramural segments (whose effect is lessened by increasing friction).

a Simple sawtooth stitch: The intramural segments are perpendicular to the wound line, and the compression zones are linear (as in simple interrupted sutures). Lateral shift vectors do not exist in the intramural segments but are very strong in the bridging segments, where they are not neutralized by opposing shift vectors or reduced by the friction of a wide compression zone. Consequently this type of suture produces a strong lateral shifting tendency when the suture line is tightened.

b Symmetrical sawtooth stitch: The intramural and bridging segments form equal but opposite angles to the wound line. The obliquity of the intramural segments determines the width of the compression zones, which are noncontiguous. In fact, the wider the compression zones, the wider the noncompressed intervals for reasons of symmetry. The lateral shift vectors of the intramural and bridging segments act in opposite directions. Though they have the same magnitude, the intramural vectors are checked by friction, so the vectors of the bridging segments predominate. There may be still a tendency toward lateral shift, therefore.

c Inverted sawtooth stitch: Here the bridging segments are perpendicular to the wound line. The compression zones of the intramural segments are contiguous and encompass the entire wound. The bridging segments, being perpendicular, have no lateral shift vectors, while those of the intramural segments are checked by friction. The result is good compression with little tendency toward lateral shift.

d Overlapping sawtooth stitch ("sharktooth" suture): Both the intramural and bridging segments are oblique to the wound line, forming angles that are equidirectional but of different size. The overlapping compression zones provide for effective wound closure. The vectors of lateral shift are equidirectional in both the intramural and bridging segments. Their "double" shifting action, however, is opposed by the increased friction produced by the "double" compressing force vectors. Also, the latter prevent the outward movement of the needle entry and exit sites that is necessary to initiate lateral shift in this type of suture



However, one side-effect of this increased tension is an increase in *undesired force vectors* that can alter the position of the wound margins. These vectors should be taken into account, therefore, when selecting the suture pattern. The *lateral shift vectors* acting in the direction of the bridging segments produce greater effects than those in the direction of the intramural (compressing) segments, because they are less constrained by friction between the wound surfaces. The effects of the lateral shift vectors in relation to the compression zones are analyzed for various suture patterns in Fig. 2.111.

The extent of the lateral shift for a given suture pattern is limited by the *suture spacing*. This makes it possible to reduce lateral wound shifting simply by shortening the interval between the stitches (Fig. 2.112).

Also, the effects of the *vertical vectors* are reduced by decreasing the *lateral distance* between the intramural and bridging segments (Fig. 2.113).

Thus, maximum compression with minimal side-effects can be achieved by using an overlapping sawtooth suture pattern ("shark's-tooth" suture) with closely spaced stitches. The compression zones in this suture overlap, so minimum tightening is required to secure wound closure (Fig. 2.111 d). Lateral shift vectors are neutralized by friction between the wound surfaces, which increases tremendously when even slight suture tension is applied (Fig. 2.111 d). Vertical vectors are neutralized by the close spacing of the stitches (Fig. 2.113).

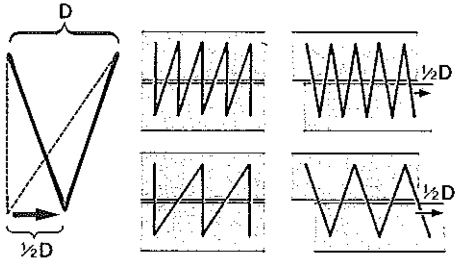


Fig. 2.112. **Relationship between lateral shift and suture spacing, illustrated for a simple sawtooth stitch.** The lateral shift necessary to produce a symmetrical stitch shape (i.e., to equalize tensions) equals half the base width *D*. Consequently, less shift occurs with closely spaced stitches (*upper right*) than with widely spaced stitches (*lower right*)

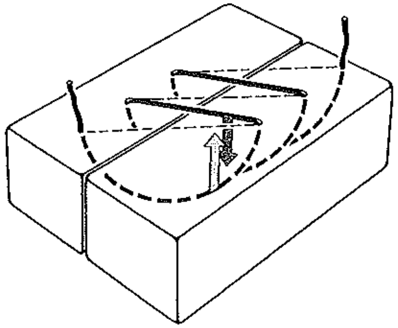


Fig. 2.113. **Effect of suture spacing on wound inversion or eversion, illustrated for the overlapping sawtooth stitch.** When the intramural and bridging segments are close together, so that they are nearly on the same plane, the tendency toward wound inversion or eversion is largely neutralized, and a smooth tissue surface is obtained

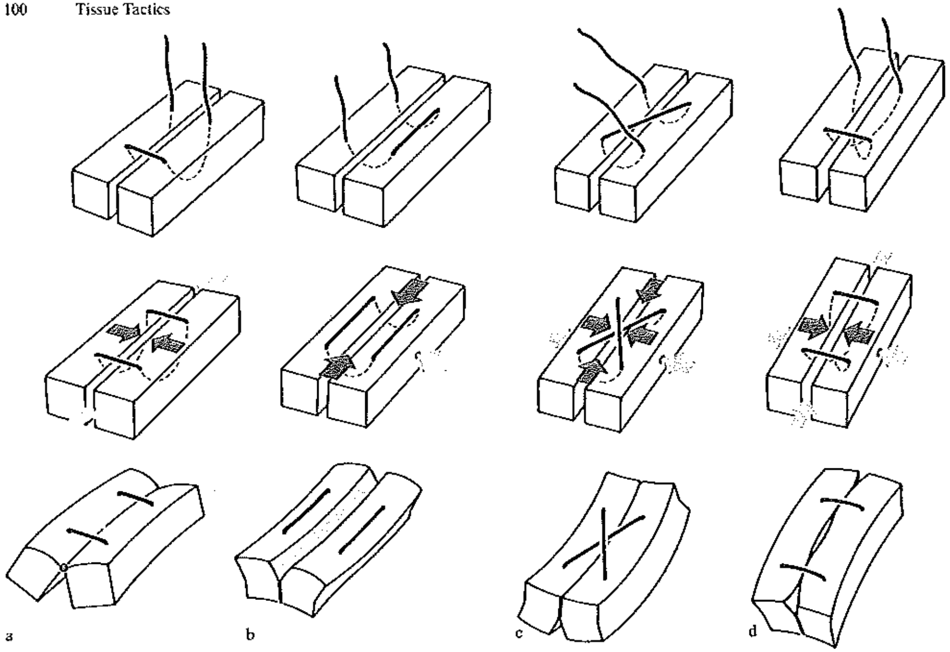


Fig. 2.114. **Mattress sutures.** The force vectors of the bridging segments are fully active (*red arrows*), while those of the intramural segments are checked by tissue resistance (*pink arrows*).

a Uncrossed inverting mattress suture: The suture bridges the wound surface but does not pierce it. No compression zones are produced. Maximum, unchecked inversion is produced transversely. A slight everting action is produced longitudinally.

b Uncrossed everting mattress suture: The intramural segments pierce the wound surface and are perpendicular to it. Significant eversion is produced transversely by deep compression of the wound surfaces.

c Crossed inverting mattress suture: The crossed portion is external, and the intramural portions are perpendicular to the wound. The bridging segment produces an inverting action both transversely and longitudinally, the transverse component being partially offset by deep everting vectors. The synergism of the deep and superficial compressing vectors effects compression which is active mainly at the superficial portions of the wound.

d Crossed everting mattress suture: The crossed portion is internal. The intramural segment is oblique to the wound surface and therefore the compression zone is broad and extends the full length of the stitch. An everting action is produced both transversely and longitudinally, the transverse component being partially offset by the inverting action of the bridging segment. The synergism of the deep and superficial compressing vector components affords good compression, which, in contrast to c, mainly affects the deep portions of the wound

Mattress Sutures

Mattress sutures are intermediate between simple interrupted sutures and continuous sutures in their function. On the one hand, they may produce *wider compression zones* than simple interrupted sutures; on the other, *local tension* can be controlled better than with simple continuous sutures.

Mattress sutures tend to produce inversion and eversion not just in the transverse direction[65] but also longitudinally.[66] These tendencies may be synergistic or antagonistic, i.e., may lead to a generalized inversion or eversion of the wound margins or a combination of both.

Uncrossed mattress sutures produce *strong inversion or eversion* of the wound edges, with little (Fig. 2.114b) or no (Fig. 2.114a) *compressive effect.*

In **crossed mattress sutures** *compression* is most effective when the stitch is crossed intramurally (Fig. 2.114d). The *side-effects* are more pronounced when the stitch is crossed on the tissue surface (Fig. 2.114c).

Countersutures

Lateral shift vectors in a continuous suture line can be completely neutralized by placing a countersuture. The opposing tensions of the double suture lines also produce a general *shortening* of the wound. But this effect is not significant if the wound is long and there is sufficient friction to resist the shortening tendency.[67]

The *compression zones* are no wider than in a single suture line. However, the *force* of the compression is increased, whether by doubling the force applied from one side of the wound (Fig. 2.115c) or by creating a counterforce on the opposite side (Fig. 2.115b).

The *vertical vectors* are neutralized in some suture patterns. This occurs at sites where the intramural and bridging segments of the two suture lines overlap (Fig. 2.115a, c). In stitches where the intramural and bridging segments do not overlap, vertical vectors are increased (Fig. 2.115b).

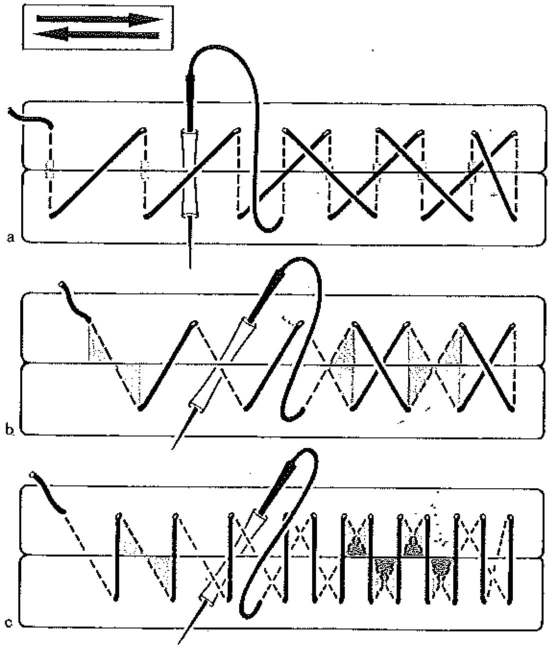


Fig. 2.115. **Analysis of countersutures**

a Double sawtooth suture: The intramural segments are perpendicular, and the compression zones are narrow, although there are twice as many of them as in the single sawtooth suture. The lateral shift vectors produced by one suture line are neutralized by the countersuture. The inverting and everting vectors also are largely neutralized because the bridging segments cross the intramural segments.

b Symmetrical double sawtooth suture: The intramural and bridging segments are oblique to the wound line. The compression zones are not wider than in a simple, symmetrical running suture (see Fig. 2.111b), but their effect is enhanced because they act on both sides of the wound. The lateral shift vectors are neutralized. The inverting and everting vectors of both suture lines are in the same segment, so their effects are additive, and the tissue surface becomes irregular.

c Inverted double sawtooth suture: The intramural segments are oblique, the bridging segments perpendicular to the wound line. The compression zones are contiguous (see Fig. 2.111c). Their force is doubled but acts on only one side of the wound at any given site. The lateral shift vectors cancel out. The inverting and everting vectors are neutralized by the superposition of the intramural and bridging segments

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[65] Caused by the vertical vectors (see Fig. 2.108).

[66] Caused by the lateral shift vectors, which tend to shorten the suture line. This effect is not checked by friction because of the short suture length, so inverting and everting components can become active.

[67] This is in contrast to the mattress suture, where the shortening effect may be significant.

Lock-Stitch Sutures

The lock-stitch suture is a continuous suture in which the thread is passed through the previous loop before the needle is reinserted.

On the one hand, such sutures have the properties of *simple interrupted sutures* in that the bridging and intramural segments are on the same plane. But they are also like *simple continuous sutures* in that they distribute tension evenly, since the individual loops are fixed only by the relatively low friction of the bridging segments.

Lock-stitch sutures have two main applications. First, they can be used like *simple running sutures* in cases where it is advantageous to equalize the tension between the individual loops (Fig. 2.116a). Second, they can be used for *tacking one tissue layer onto another* (Fig. 2.116b).[68] This technique utilizes the compressive effect not of the loops but of the linking segments.

Lock-stitch structures differ from simple running sutures in that the wound edges do not shift laterally when the suture is pulled tight. The tightening causes a *shortening of the linking segments* which, as they tend toward linearity, are forced onto the shortest path connecting the two ends of the suture. This tendency can be utilized to adjust the position of the linking segments by appropriate angling of the suture (Fig. 2.117).

In a **meandering suture** the position of the linking segments is fixed. The *intramural* segments produce an *everting* effect, while the *linking* segments can be used for tacking, as in the lock-stitch suture. In their *simple form*, meandering sutures have discontinuous overlying segments. In the *reverse form* the overlying segments form a continuous zone whose position is fixed and not altered by suture tension (Fig. 2.118).

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[68] Example: Tacking a conjunctival flap to the cornea or sclera (see also Figs. 4.26–4.28).

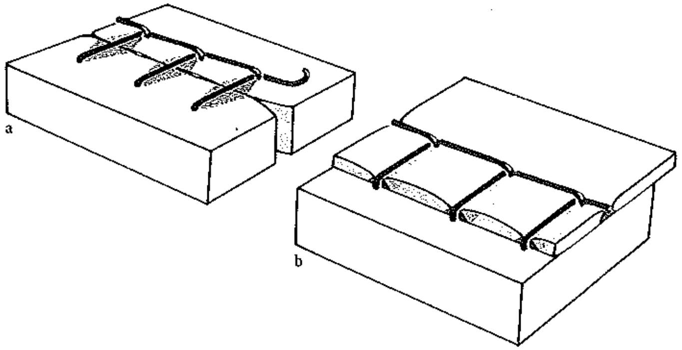

Fig. 2.116. **Applications of a lock-stitch suture**

a *Compression suture*, whose tension can be regulated by adjusting the tension of the linking segments. The compression zones are like those produced by simple interrupted sutures (see Fig. 2.109).

b *Tacking stitch*: The bridging segments are used to form a broad, continuous compression zone (*pink*) that can fix one tissue layer to another

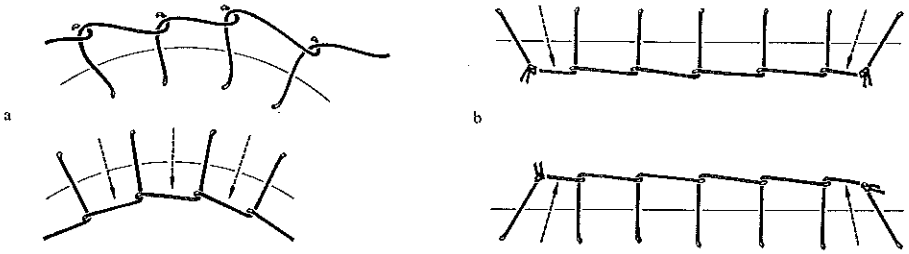

Fig. 2.117. **Behavior of a lock-stitch suture on tightening.** When the suture is tightened, the linking segments are forced onto the shortest connecting line.

a On curved wound lines (*above*), the linking segments are drawn toward the center of curvature (*below*).

b On straight wound lines, the position of the linking segments is controlled by angling the ends of the suture to shorten the upper or lower connecting line

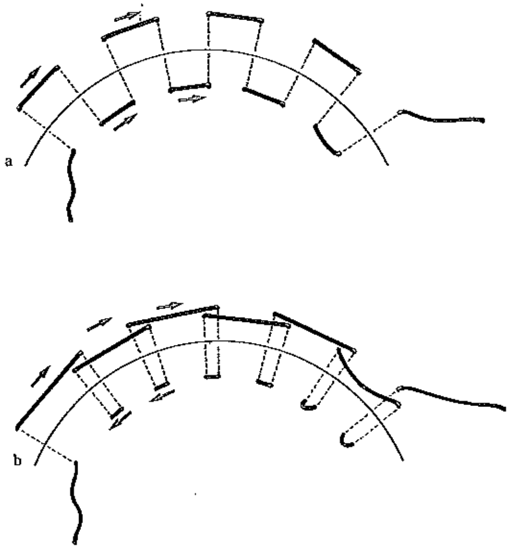

Fig. 2.118. **Meandering sutures**

a The linking segments are discontinuous in this stitch, and they do not change their position when tightened.

b The reverse meandering suture creates a continuous, overlapping series of linking segments

Relationship of the Suture and Needle Track

If the needle has a larger diameter than the suture material, the needle track also will have a larger diameter. This may allow the suture to shift inside the track, and the wound edges may shift relative to the splinting material (Fig. 2.119).

This means that when a thin thread is pulled tight inside a larger needle track, it will assume a *position* that may be *different from that which the surgeon intended* and defined by his guidance actions. The thread is forced onto the shortest connecting path, which may lie closer to the surface, wound margin, or adjacent suture depending on the cross-section of the track (Fig. 2.120). The final thread position is especially difficult to predict if the needle track is oblique, but it can be estimated beforehand by a tensile test (Fig. 2.125) and corrected to some degree by modifying the thread tension.

Shifting of the thread within the needle track allows thread shortening with no consequent tissue deformation and can even serve to correct minor deficiencies in the placement of the track (Figs. 2.121, 2.122). However, the discrepancy between the intent of the surgeon (guidance of needle tip) and the result (position of the thread axis) carries a risk of faulty apposition. When thin threads are used, therefore, their shifting tendency must be anticipated and allowed for when selecting the needle (which determines the cross-section of the track, see Fig. 2.91).

The *splinting action* of thin threads is likely to improve during the course of wound healing as the needle track gradually cicatrizes and its cross-section approaches that of the suture. A process with the *opposite effect* may also occur, however: The track may dilate due to an inflammatory response which varies in intensity with the tissue compatibility of the suture material

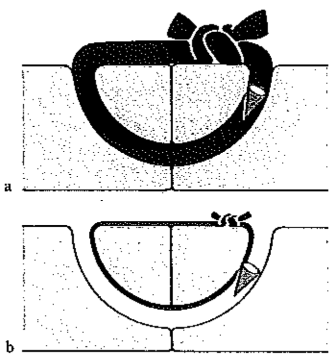

Fig. 2.119. **Disparity in the diameters of the suture and needle track**

a A suture acts as a splint if the thread size matches the lumen of the needle track. In this case the thread axis equals the path of the needle tip (*red*) and coincides with its guidance direction.

b If the thread is much thinner than the needle track, its final position is not on the path of the needle tip but on the shortest connecting path

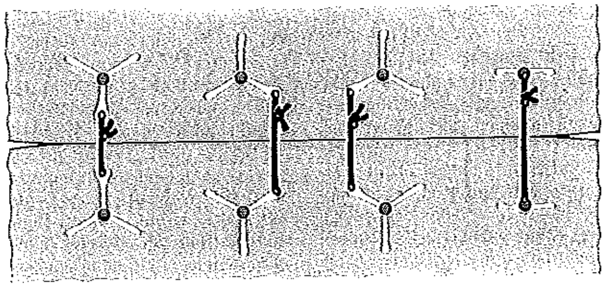

Fig. 2.120. **Shifting of thin threads in the needle track.** The shortest connecting path within the track varies with the cross section of the track. In the track cut by a triangular needle (see Fig. 2.91), the thread shifts away from the path of the needle tip (*red*), moving closer to the wound margin (*left*) or into one of the side arms (*center*). In a slitlike track (*right*) the thread remains centered only if the track is exactly perpendicular to the wound line

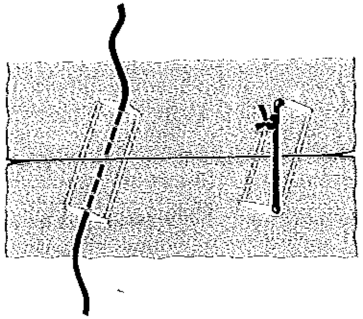

Fig. 2.121. **Shifting of thin threads in an oblique needle track.** When a thin thread is tightened in an oblique needle track, vector components parallel to the wound margin tend to force the thread onto a path perpendicular to the wound. If the needle track is wide enough, the thread may shift with no associated shifting of the wound edges ("self-correction of oblique thread placement")

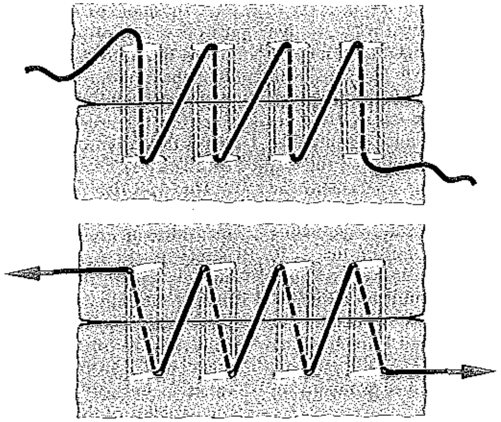

Fig. 2.122. **Shifting of thin threads in a continuous suture line.** In a simple sawtooth suture (*top*), tension can equalize spontaneously by the shifting of the thread in its track (*bottom*). This avoids any lateral shifting of the wound edges

Table 2.1

	 A Wire	 B Twine	 C Sheathed twine
Surface	smooth	rough	smooth
Flexibility	low	high	high
Distensibility	depends on material	good	depends on material and thickness of sheath
Tissue compatibility	good	fair	good

Generally it may be assumed that commercially available suture materials have good tissue compatibility. For a given material, the thinner, smoother and more flexible the thread, the better its compatibility.

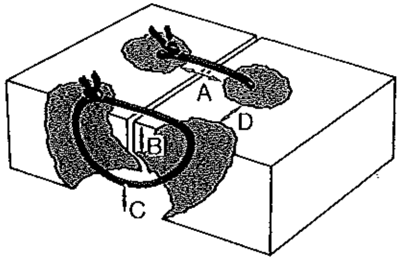

Fig. 2.123. **Effect of the inflammatory canal on suture spacing.** The development of an inflammatory canal shortens the distance from the suture tract to the wound margin (*A*), outer tissue surface (*B*), inner surface (*C*), and adjacent sutures (*D*). Hence, with sutures that incite an inflammatory response, larger values must be chosen for A, B, C, and D than with a nonirritating suture material

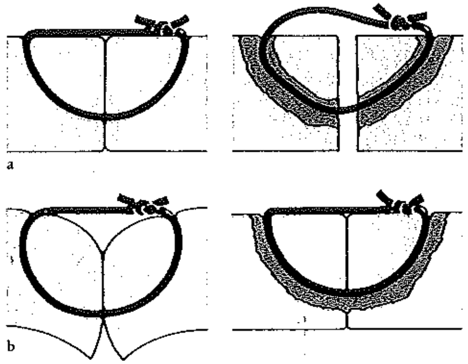

Fig. 2.124. **Effect of inflammatory canal on wound approximation**

a Threads correctly placed initially (*left*) are loosened by expansion of the suture track in the postoperative period, and wound approximation is lost (*right*).

b The wound deformation caused by overtightened threads (*left*) is spontaneously relieved by the loosening effect of the inflammatory canal (*right*): "Self-adaption of overtightened sutures"

(Table 2.1), and an "**inflammatory canal**" may develop around the thread (Fig. 2.123). This process can be favorable, however, in that it can loosen overtight threads as healing progresses and thus reverse the initial tissue deformations caused by compression sutures (Fig. 2.124).

The possible formation of an inflammatory canal should always be considered in the operative plan, for it influences the **selection of suture material**. Sutures placed close to the wound edges, tissue surface, or adjacent sutures should be made of a *nonirritating* material.[69] On the other hand, compressing sutures that produce primary tissue deformation may be made from a mildly *irritating* material so that the subsequent tissue reaction and loosening effect will correct the initial deformation.[70]

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[69] Example: Monofilament polymer.

[70] Example: Twisted, braided or coated silk.

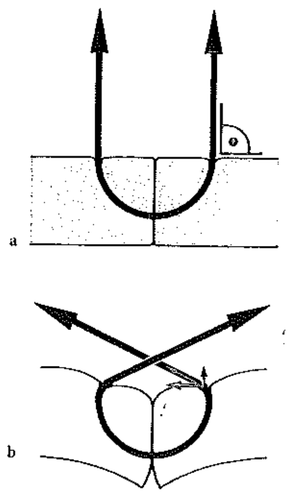

Fig. 2.125. **Effects of suture tightening**

a The distance between the entry and exit sites of the suture is not affected by pulling the ends of the thread vertically upward.

b If the suture ends are pulled together during tightening, vectors form in the direction of the wound margins, and the entry and exit sites move closer together

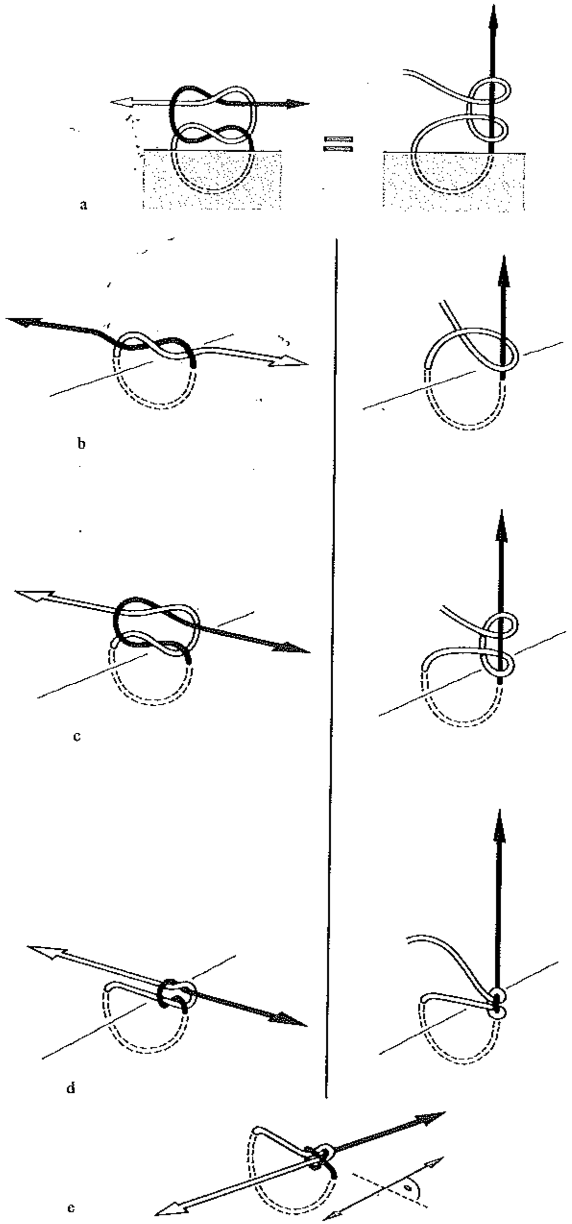

Fig. 2.126. **The square knot and slip knot** ►

a Starting with the same initial loop arrangement, a simultaneous horizontal pull on both ends of the thread makes a square knot (*left column*), while a vertical pull on only one end makes a slip knot (*right column*).

b Making the approximating loop: The square knot (*left*) is already in the correct position; the slip knot (*right*) is still loose.

c Making the securing loop.

d Positioning the knot.

e The securing loop is tightened at right angles to the suture plane so that it will not affect the established suture tension

Knots

When a suture is tied, all forces should be applied so that the position of the wound edges is not changed. The *rule of vector separation* is helpful for avoiding vector components directed toward the wound line: Tightening the thread in the needle track is done separately from the tying maneuver (Fig. 2.125), and the direction of pull on the securing loops is at right angles to that on the approximating loops (Fig. 2.126e).

The **holding strength** of knots depends largely on the *friction* that is created within the tightened loops. Hence the quality of the suture material plays an important role: its surface roughness, compressibility, and flexibility. The less friction produced by the material, the greater the contact area that must be established by the knotting technique.

The first loop, called the *approximating loop*, performs the actual suturing function: It apposes and fixes the wound edges in the desired position. All *additional loops* serve only to secure the approximating loop.

In **square knots** the approximating loop is first placed in its definitive position and held there while the securing loop is tied (Fig. 2.126 *left*). In **slip knots** the approximating and securing loops are first tied loosely and then drawn together into the correct position (Fig. 2.126 *right*). Both knots can be tied from the same initial loop arrangement, and only the direction of traction on the threads determines which type of knot will result.

The knot preferred in a given case depends largely on the *frictional characteristics* of the suture material. *Rough threads* favor square knots because their high friction holds the approximating loop in place. They make poor slip knots, because the knots may close before they are correctly positioned. In contrast, *smooth threads* are easily

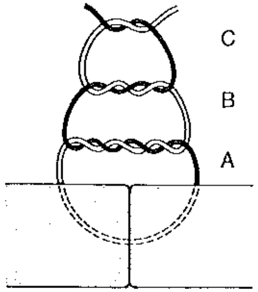

Fig. 2.127. **The reinforced knot**

A Approximating loop. *B, C* Securing loops.

A The friction that maintains the position of the approximating loop until the securing loops are tied can be increased by passing the thread through the loop several times (here: Three).

B If the first securing loop were much shorter than the approximating loop, it would deform it, and in elastic suture material the resulting forces could reopen the knot. To make the loop lengths more equal, the thread is also passed repeatedly (here: Twice) through the securing loop.

C With stiff suture material, a second securing loop can be placed to reinforce the first

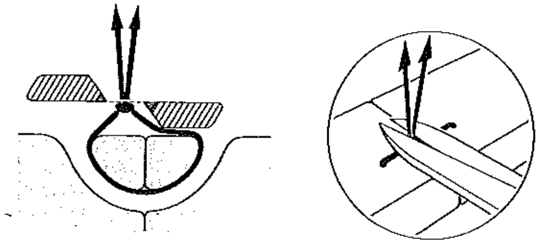

Fig. 2.128. **Cutting the ends of the thread close to the knot with a scissors.** The knot is pulled up against the cutting point, the degree of traction depending on the thickness of the blades. Since the knot is hidden behind the scissors, the best view is obtained by cutting with the tips of the blades

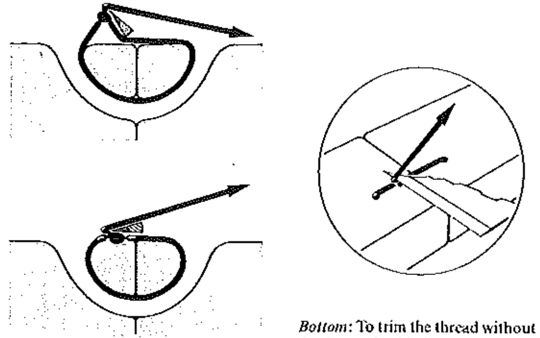

Fig. 2.129. **Cutting the ends of the thread close to the knot with a razor blade tip**

Top: If loop tension allows the thread to be pulled upward slightly, the blade can be angled to improve vision. The knot is pulled up against the cutting edge, the ends of the thread are stretched over it and, with the blade stationary, are snapped off with a quick tug.

Bottom: To trim the thread without raising the loop, the blade is laid flat over the knot, its cutting edge flush with the edge of the knot. Then the end of the thread is drawn back and snapped off with a quick tug. It is not necessary to see the knot in this maneuver, since the relation between the cutting edge and edge of the knot is precisely established before cutting and remains unchanged when the thread is cut

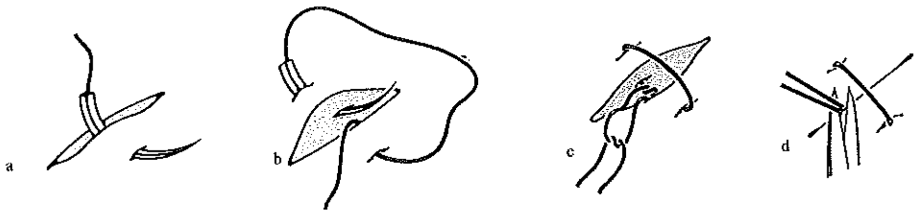

Fig. 2.130. **Burying the knot in a simple interrupted suture**

a, b The needle is inserted through the wound surface from the inside, brought out, then reinserted into the second wound surface from the opposite side. It can be difficult to pierce the second wound surface at a site exactly opposite the insertion site, but in case of thin suture material in a larger needle track any lack of precision in wound approximation may be remedied by "self adaption" (see Fig. 2.121).

c The knot is tied between the wound surfaces.

d The thread ends are cut flush with the tissue surface

tied into slip knots but are not good for square knots because the approximating loop tends to loosen before the securing loop is tied. The friction can be increased by passing the thread repeatedly through the loops, but of course this results in a bulkier knot (Fig. 2.127).

Knots left on *tissue surfaces* are a source of irritation, but this can be minimized by clipping the threads as close to the knot as possible (Figs. 2.128 and 2.129).

If the suture material is sufficiently tissue-compatible, the knot may be buried within the tissue. Either the stitch is begun from inside the wound (Figs. 2.130 and 2.131) or, if the threads are so fine that the knot is much smaller than the lumen of the needle track, the knot may be pulled into the track after it is tied (Fig. 2.132).

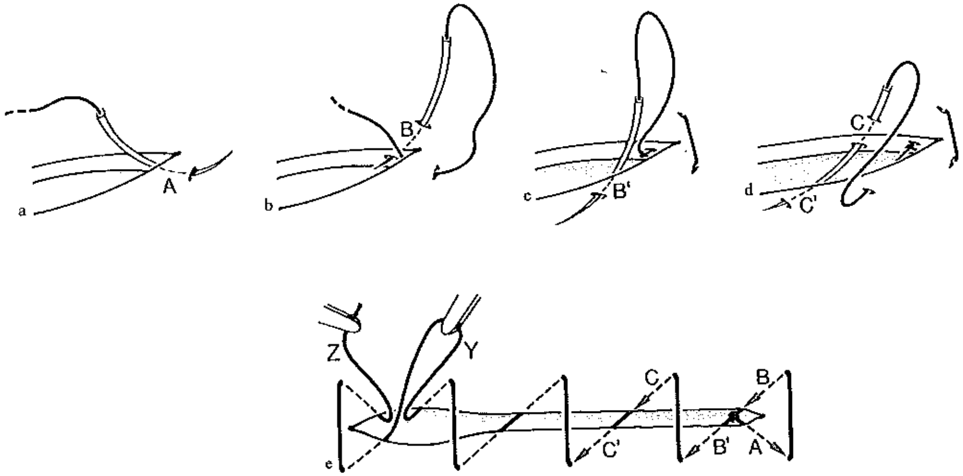

Fig. 2.131. **Burying the knot in a continuous suture**

a The needle is inserted from inside the wound and brought out at a point (*A*) past the end of the incision (see Fig. 2.110a).

b The needle is reinserted at a corresponding point on the other side of the incision (*B*), piercing the opposing wound surface at a point opposite the original insertion site.

c The suture is tied, and the needle is reinserted through the wound surface and brought out at *B'*.

d Continuation of the running suture.

e The final stitch is made past the end of the incision, as in a. The final knot is tied between a loop brought out from the wound surfaces at *Y*, and the end of the thread (*Z*)

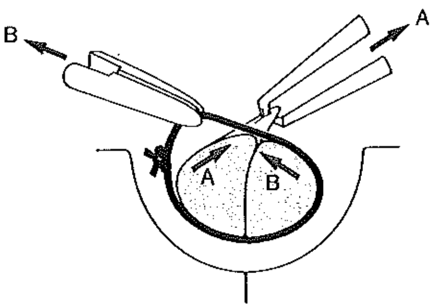

Fig. 2.132. **Advancing the knot into the suture tract.** The tissue encircled by the loop is compressed briefly so that the knot can slip over the step at the entrance to the track. This is done by pulling on the thread (*B*) while applying countertraction with a forceps (*A*)

2.2 Application of Heat

The application of heat to tissue raises the temperature of the tissue and alters it by *coagulation*, *shrinkage*, or *carbonization*. An effect that is desired at one site may be deleterious at another.[71] Accordingly, the control of heat application consists in achieving a precisely defined *temperature* within a precisely defined *tissue volume* at a specified *location*.

The desired temperature is achieved by delivering a specific quantity of heat to the target site. This heat may be produced outside the tissue and then *transferred* to it via a conductor, or it may be *generated* within the tissue itself (Fig. 2.133).

The preferred **technique of application** depends on the size of the tissue volume to be heated and on whether a superficial or deep effect is desired. Techniques suitable for some tasks may be inappropriate for others, producing a greater- or less-than-optimum effect. For example, a technique suitable for heating a large tissue volume would produce over-effect in a smaller volume.

Two physical processes that complicate the precise **control** of tissue heating are *conduction* and *convection*.[72] Since both parameters change during heat application, control based on digital readouts (temperature of a cautery or cryode, voltage of a diathermy current) is not reliable. The only way to monitor heat application is by noting the visible effects on the tissue and regulating the heat input accordingly. Thus, control is effective only in cases where the tissue changes can be observed directly or by ophthalmoscopy.

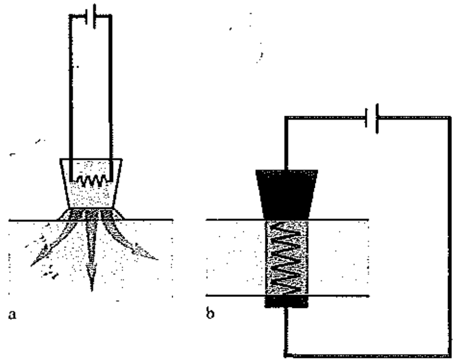

Fig. 2.133. **Methods of heating tissue**

a Transmitting heat to the tissue: Heat produced outside the tissue is transferred to the target site. The critical factors are thermal conductivity and heat capacity.

b Generating heat in the tissue (diathermy): The heat is generated at the target site. The critical factors are the electrical properties of the tissue

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[71] For example, hemostasis (shrinkage of vessel walls and coagulation of their contents) should not affect surrounding tissues to the extent that wound edges are deformed and reapproximation is impaired. Hence, deep effects must be avoided, and intraocular structures must be spared. On the other hand, deep effects are desired when aseptic inflammatory lesions are induced as a stimulus for scar formation (retinal detachment surgery, obliteration of the ciliary body in glaucoma surgery). In these cases excessive shrinkage of the sclera should be avoided because it could unduly raise the intraocular pressure. However, scleral contraction is necessary to produce wound dehiscence in fistulating glaucoma operations. Carbonizing temperatures are used only for the actual division of tissue.

[72] The coefficient of heat *conduction* is a material constant which, in tissues, depends basically on moisture content; it is reduced by drying. *Convection* refers to heat transfer by fluids in motion. In homogeneous tissues it depends mainly on blood flow; thus it is decreased by compression or coagulation of the vessels. Convection at surfaces is effected by free-moving fluid layers.

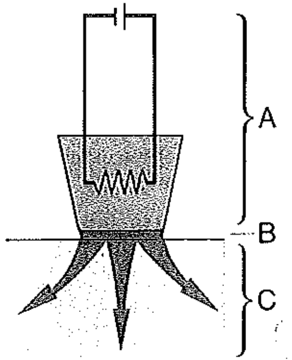

Fig. 2.134. **The heat transfer chain.** *A* Heat source. *B* Transfer resistance (tissue surface). *C* Dissipation and elimination (tissue)

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Fig. 2.135. **Large-capacity heat source (spherical cautery).** Large dimensions = large capacity. This instrument requires a relatively long reheating time in air after it has transferred its heat to the tissue

Fig. 2.136. **Small-capacity heat source (wire loop).** Small dimensions = small capacity. This instrument transfers all its heat to the tissue upon contact, so control is difficult. Since a small capacity implies high temperatures, there is a danger of overheating at the tissue surface

2.2.1 Heat from an External Source

Heat is carried into and out of tissue in a "heat transfer chain" (Fig. 2.134) consisting of *heat production* (temperature and heat capacity of the source), *transfer* (transfer time and resistance to transfer), and *elimination* (convection).

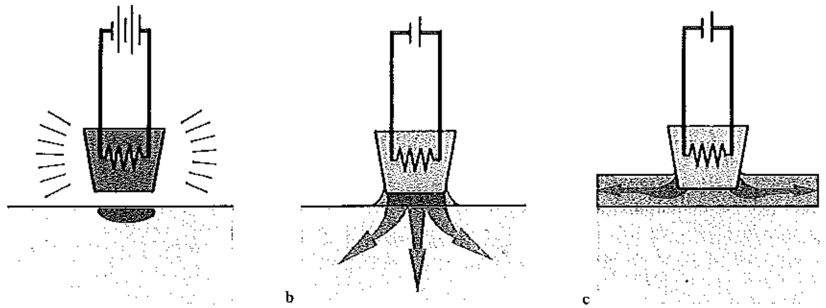
Heat Production. Energy is invariably lost during transfer, so a *heat surplus* must be delivered by the source. This is done either by supplying an excessive quantity of heat at a precisely regulated temperature (large-capacity cautery, Fig. 2.135) or a small quantity of heat at a higher temperature (small-capacity cautery, Fig. 2.136).

Application of the precise temperature protects the tissue from overheating, but there may be insufficient space for an applicator of *large capacity*. *Small-capacity* applicators eliminate this problem but pose a danger of over-effect due to excessive temperatures.

Heat Transfer. Heat application is controlled most effectively by varying the transfer parameters of time and resistance. Limiting the **application time** avoids tissue overheating when excessive temperatures are used. Dabbing the target site briefly and repeatedly with the applicator allows the heat to be applied in a "digital" rather than analog fashion.

The **transfer resistance** of the tissue is a function of its moisture content. If the tissue surface is *dry* (Fig. 2.137a), the heat cannot penetrate to deep levels, and its effects will be superficial (which further increases the transfer resistance and the risk of over-effect). *Moist* surfaces allow for better heat conduction and are necessary for deep penetration (Fig. 2.137b). However, a *continuous liquid film* dissipates heat and lessens its effect on the tissue (Fig. 2.137c).

Fig. 2.137. **Methods of controlling transfer resistance**
a Heating the cautery in air. The transfer resistance is very high, and the cautery becomes very hot through retention of heat. Heating of the surrounding air dries the tissue surface, increasing its resistance to heat transfer. If the cautery is then applied to the tissue the effect is continued to its surface (danger of over-effect).
b Moistening the surface improves heat transfer to the tissue and thus enhances the deep effect.
c A thick fluid layer dissipates the heat and diminishes its effect on the tissue



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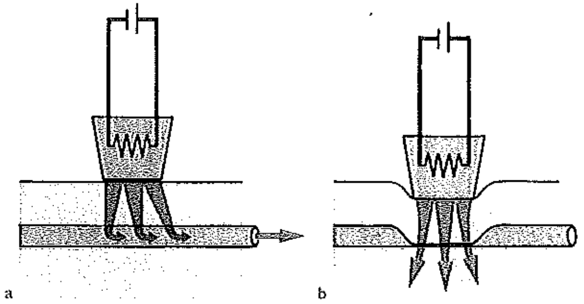
Heat Elimination. Because most heat is removed from tissue by *fluid motion*, heat elimination can be controlled by varying the *blood flow* through the affected area. The surgeon can lessen the rate of heat elimination by exerting pressure on the applicator. This produces vascular compression either directly or indirectly by raising the intraocular pressure (Fig. 2.138).

Technique of Application. The application technique involves adapting the supplied quantities of heat to the volume of tissue that is to be heated. The volume is small in very *circumscribed surface coagulation* (Fig. 2.139a), larger in the heating of *larger surfaces* by dynamic coagulation (Fig. 2.139b), and largest in *deep coagulation*, where a continuous heat influx is maintained (Fig. 2.139c). Thus, the different application techniques are appropriate for different heating requirements. A combination of different techniques is difficult to control unless the heat input (cautery temperature) is separately adjusted for each.

Fig. 2.138. **Control of heat elimination**
a Heat is eliminated from the tissue via the bloodstream.
b Compression of the vessels interrupts the blood flow and increases the thermal effect by reducing heat loss

Fig. 2.139. **Modes of application of heat transmitters**
a *Surface coagulation* (*static*): The applicator is preheated and applied warm to the tissue. All heat is transferred in a circumscribed area; transfer is controlled by regulating the temperature.
b *Surface coagulation* (*dynamic*): The preheated applicator is moved back and forth on the tissue surface. Larger quantities of heat (= higher temperatures) are required than in the static method, and transfer is controlled by the speed of applicator movement.
c *Deep coagulation*: The applicator is placed onto the tissue before it is heated. Heat flows into the tissue during warmup, and some time is required for the onset of effect. Large quantities of heat are needed. The effect is difficult to assess



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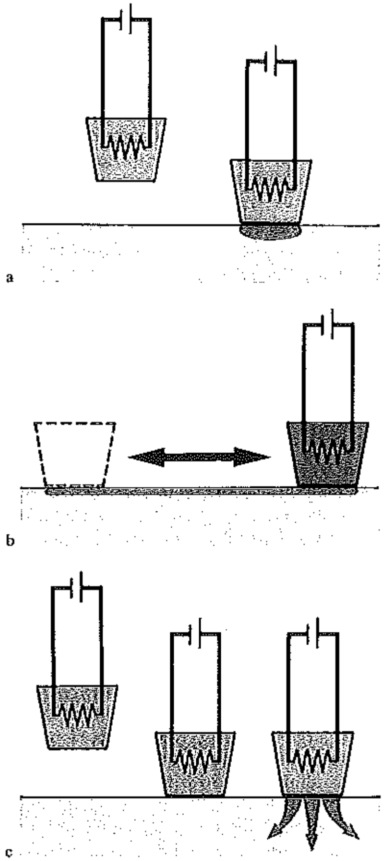

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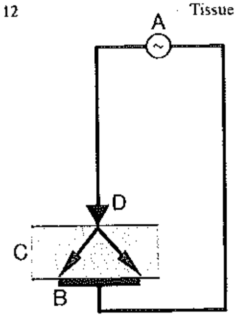

Fig. 2.140. **Electric circuit for generating heat in tissue.** *A* Voltage source. *B* Indifferent electrode. *C* Tissue resistance. *D* Active electrode

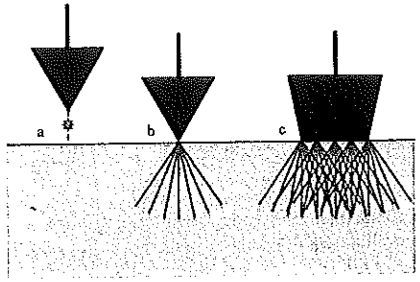

Fig. 2.141. **Contact between the active electrode and the tissue**

a If a high voltage is applied prior to tissue contact, a spark will form (with danger of tissue destruction).

b Pointed electrodes concentrate their energy at the site of application (surface).

c Flat-faced electrodes also produce a high current density at deeper levels

2.2.2 Heat Generation in Tissues

Diathermy

Heat is generated in tissues by an electric circuit consisting of the *voltage source*, the *indifferent electrode*, the *electrical resistance* of the tissue, and the *active electrode*. The voltage source delivers alternating current in a frequency range appropriate for the generation of heat. The **indifferent electrode** should be as large as possible to minimize the current density at that location (Fig. 2.140).

The **electrical resistance** for a given diameter and spacing of the electrodes is determined by the *electrolyte content* of the tissue. Hence it can vary during coagulation.

The **shape of the active electrode** determines the extent of tissue contact and thus the distribution of current density in the tissue (Fig. 2.141). As the *contact area* increases, the current density rises at deeper levels, but higher voltages are also required. If the same electrode is applied "at a point" in one instance and over a larger area in another (Fig. 2.142), the voltage must be adjusted accordingly.

The technique of application depends on whether the effect should be superficial or extend to deeper levels. Superficial heating is achieved by using a pointed electrode on a dry surface. Deeper heating is promoted by a moist tissue surface and a broad electrode. Of course, the limits of heat production cannot be precisely defined, and variations in the electrical properties of tissues can always lead to undesired deep effects that are not appreciated by observing the tissue surface.

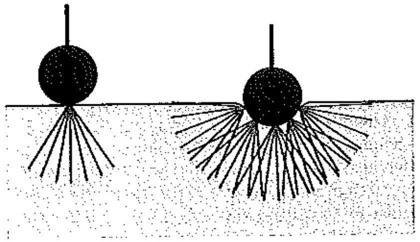

Fig. 2.142. **Spherical electrodes.** A sphere can have the same effect as a pointed or flat-faced electrode, depending on the pressure of application. The voltage must be adjusted accordingly

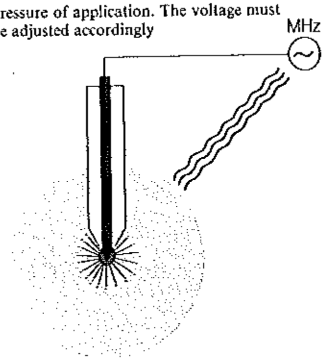

Fig. 2.143. **Unipolar miniprobe.** The heating effect is extremely concentrated owing to the high voltage and sharply pointed tip of the active electrode. A separate indifferent electrode is not required. The alternating current is returned in the form of radio waves from the patient's body (which acts as an antenna) to the current source

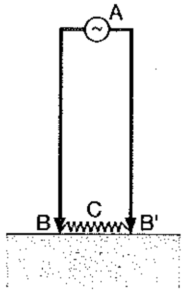

Fig. 2.144. **Electric circuit for bipolar diathermy.** *A* Voltage source. *B* and *B'* Active electrodes. *C* Heat-generating resistance

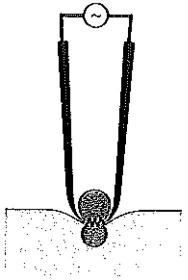

Fig. 2.145. **Direct bipolar diathermy of tissue.** The tissue grasped between the forceps blades is heated

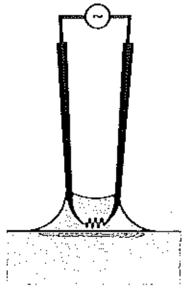

Fig. 2.146. **Indirect bipolar diathermy through a liquid film.** An electrolyte-containing liquid is heated and forms a heat-transfer medium

Miniaturized diathermy probes: Applicators with a highly localized diathermy effect are required for intraocular use. The unipolar miniprobe (Fig. 2.143) functions without an indifferent electrode. Increasing the frequency to the megahertz range produces a tremendous concentration of energy at the pointed tip of the active electrode. The energy falls off rapidly with distance from the tip, allowing for highly selective intraocular coagulation. However, remote effects may still occur as a result of impedance variations: Tissues with a low water content have a higher impedance than water-rich tissues. Other side-effects can result from stray currents induced by the presence of air bubbles in the eye or the introduction of other instruments (vitrectomy probe, fiberoptic light, etc.) into the eye.

Bipolar Diathermy

Bipolar diathermy can be used to *generate heat* in tissues as well as to *transmit heat*.

The voltage in bipolar diathermy is produced between *two* slender, identically shaped *active electrodes* (Fig. 2.144), which either grasp the tissue to be coagulated (Fig. 2.145) or are immersed in a liquid film on the tissue surface (Figs. 2.146, 2.149).[73]

When the electrodes are applied **directly to the tissue**, they act as a *diathermy*. Control is difficult, because as soon as an effect is achieved, the critical parameters are altered as a result of tissue contraction, approximation of the forceps blades, and increased resistance due to drying. Continued application will produce over-effects, so the margin between effect and over-effect is very slim.

By contrast, a very large safety margin is provided by **indirect application** where the electrodes are immersed in an electrolyte-containing film (e.g., physiologic saline) (Figs. 2.146, 2.149). The liquid film provides an *ideal heat-transfer medium* whose temperature is limited by its boiling point and whose transfer resistance remains low and constant.

The energy release is *controlled* either by changing the voltage (Fig. 2.147) or changing the electrode spacing (Fig. 2.148). When bipolar diathermy is applied in the direct mode, the energy should be released in short bursts because of the small safety margin. Indirect application requires a more prolonged energy release due to the greater length of the heat-transfer chain (which includes the liquid film). An additional means of control is the use of irrigation to dissipate heat (Fig. 2.150).

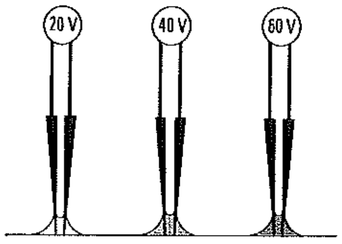

Fig. 2.147. **Control of diathermy by changing the voltage.** The electrode spacing is kept constant

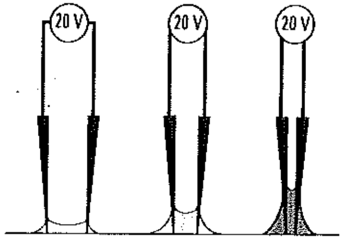

Fig. 2.148. **Control of diathermy by changing the electrode spacing.** The voltage remains constant

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[73] Caution: Touching the forceps tips together while the voltage is on will cause a short-circuit, and the tips will fuse.

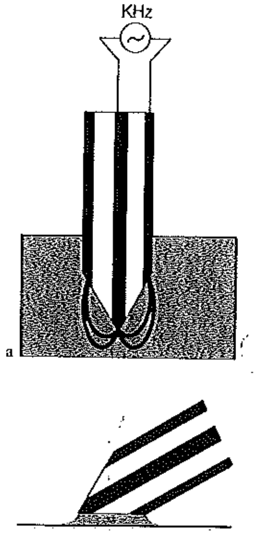

Fig. 2.149. **Bipolar miniprobe**

a The bipolar probe consists of a thin, pointed active electrode sheathed by an indifferent electrode and separated from it by an insulating layer. A current flows only when both electrodes are immersed in fluid. The heat produced is transferred to the environment.

b Surface coagulation: The probe is held obliquely in a thin fluid film so that both the tip and part of the sheath electrode are immersed in the conductive fluid layer

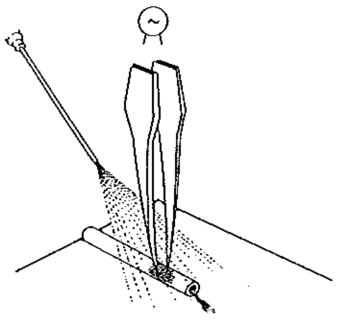

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Fig. 2.150. **Indirect application of bipolar diathermy,** illustrated for the coagulation of a bleeding vessel. Heat dissipation is controlled by irrigating the surface during the coagulation. This prevents the large quantity of heat from spreading to deeper levels

2.2.3 Application of Cold

Cryofixation uses the cryoprobe as a mechanical *grasping instrument* by forming an ice ball that is continuous with tissue structures. The instrument exerts no pressure on the tissue and therefore causes no deformation on grasping. It can even grasp tissues whose cohesion is poor when the ice ball, whose cohesion is strong, extends to deeper levels. The disadvantage of cryofixation is that the ice mass can inadvertently encompass neighboring structures.

Deep freezing produces controlled *tissue damage* (localized aseptic inflammation) without the side-effects that are associated with the application of heat (coagulation necrosis and connective tissue shrinkage).

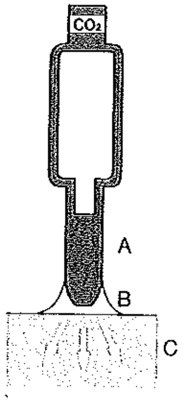

Fig. 2.151. **The cold transfer chain.** *A* Cold source (cryoprobe). *B* Transfer resistance. *C* Dissipation and elimination in the tissue

The **cold source** is a cryoprobe (Fig. 2.151), which induces freezing by evaporative cooling (change from a solid or liquid to a gas) or by the rapid expansion of gases (Joule-Thomson effect). Different cryoprobes differ mainly in their means of control, temperature, and associated technical costs. In *superficial freezing*, where the effect is produced by cooling the tissue below a threshold temperature (onset of freezing), further lowering of the probe temperature affects only the rate of the process. In *deep coagulation*, on the other hand, the tissue effect correlates with temperature, so it is necessary to determine the temperature on the basis of relevant biologic data.

The **resistance to cold transfer** basically depends on the same factors that govern heat transfer (Fig. 2.152). But the resistance may be increased by the ice mass itself, which acts as an *insulator* to retard further cold transfer from the probe to the tissue.

Ice formation in tissues depends on their *moisture content* (conduction and convection) and *electrolyte content* (freezing point). Freezing is tissue-specific, therefore, and may proceed at different rates in adjacent tissues. Thus, ice formation observed in a particular tissue layer does not necessarily signify analogous freezing of other parts.[74] These differences in freezing tendency can be utilized tactically as a means of grasping solid bodies in a liquid medium.[75]

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[74] Examples: Ice formation in the relatively dry lens capsule does not necessarily mean that ice has formed in the interior of a water-rich lens (intumescent cataract, hypermature cataract). Also, the size of the ice spot on the surface of the sclera does not indicate the extent of freezing of the uvea or retina (due to interference by vascular heat conduction in the choroid).

[75] Example: Dislocated lens in the fluid vitreous.

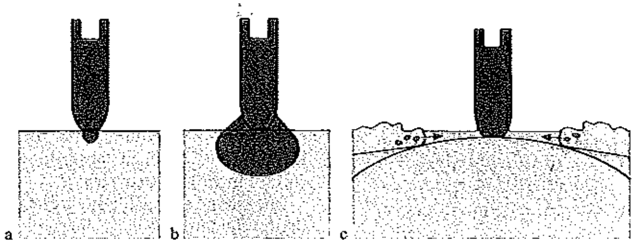

Fig. 2.152. **Control of transfer resistance**

a A dry surface has a high resistance, and very little ice forms in the tissue.

b Moist surfaces lower the transfer resistance. A large ice ball forms attaching the cryoprobe to the tissue.

c A liquid film conveys heat from surrounding structures, retarding ice formation

In the practical application of cold (Fig. 2.153), the *deepest penetration* is achieved when the probe is brought in contact with the tissue before it is activated. If the probe is cooled in the air before it is applied, it will acquire a frost coating that insulates against cold transfer, restricts the effect to the tissue surface, and thus provides poor adhesion for grasping.

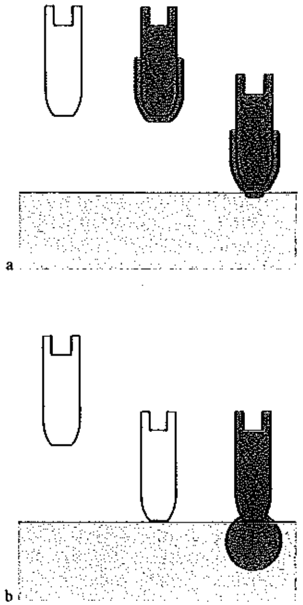

Fig. 2.153. **The application of cold**

a A cryoprobe cooled in air acquires an insulating ice film that hinders cold transmission to the tissue.

b Activating the cryoprobe only after it is applied causes a progressive temperature drop in the tissue. The penetration depth is greater, but more time is required for formation of the ice ball

2.3 Application of Light

The transport chain for heat production by concentrated photon energy consists of a *light source*, *light path*, and *heat transfer* within the tissue.

The properties of the light path determine the effect of the light. Interaction between the photons and substrate should be *minimal* on the *transmission path* leading up to the target but *maximal* at the intended site of action.

The **energy density** (power density) is controlled by focusing. Precision is highest when the energy density falls off sharply in the zones directly adjacent to the target (Fig. 2.154). This is accomplished by using an optical system that projects a highly *convergent beam* (Fig. 2.155).

The *eye* itself forms a major portion of the light path. Optical imperfections in the transparent ocular media (whose effects are additive with increasing depth) limit the accuracy of beam focusing. For best results, then, the *delivery optics* (e.g., contact lenses) must be precisely calculated for the specific site in the eye to which the energy is to be delivered.

For a given beam, increasing the *size of the light spot* at the target reduces its energy density since the total energy must remain constant. Thus, to maintain a predetermined energy density, a larger spot size requires a corresponding increase in the energy input.[76]

Absorption and transmission of the beam in a given substrate are a function of *wavelength*. Each tissue displays a *spectral selectivity*

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[76] In purely geometric terms, the energy input should increase with the square of the spot diameter. But as far as the resulting effects are concerned this is only a rough guideline since increasing the spot size alters its ratio of area to circumference, and this affects heat dissipation.

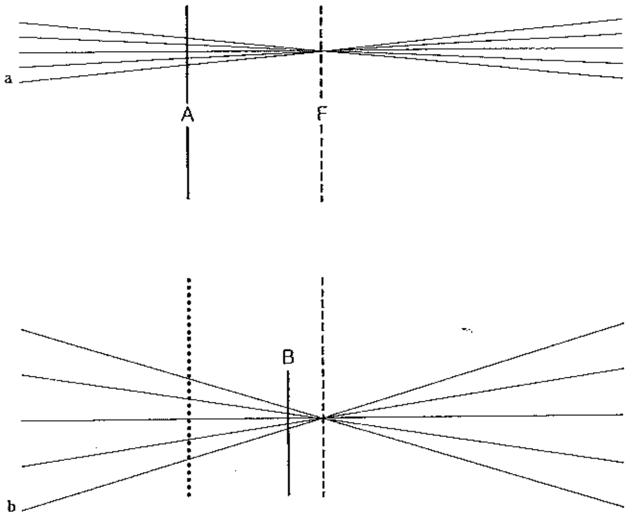

Fig. 2.154. **Energy density of light beams**

a In a weakly convergent beam, the energy density is still high some distance (*A*) from the focus (*F*).

b In a strongly convergent beam, the energy density falls rapidly with distance from the focus. Thus, the energy density at distance *A* is substantially lower than in Fig. a, and the site with the same density lies closer to the focus (*B*)

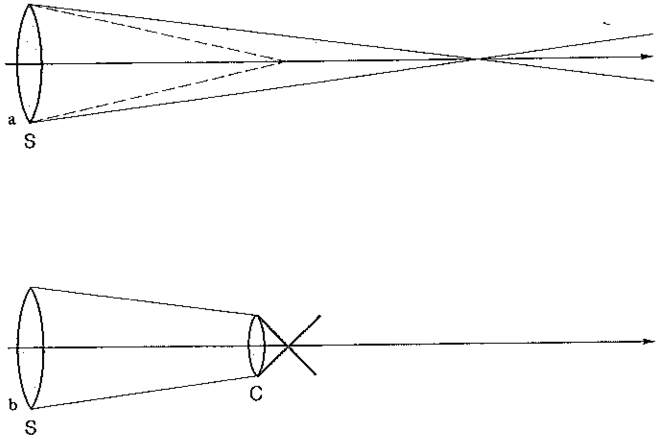

Fig. 2.155. **Focusing a light beam**

a Increasing the convergence of a light beam emerging from the optical system of an energy source (*S*) requires a reduction of the "working distance" between *S* and the focus (*hatched line*)

b Convergence can be increased further by placing additional optics (*C*) in front of the target (e.g., placing a contact lens with a convex surface on the corneal surface)

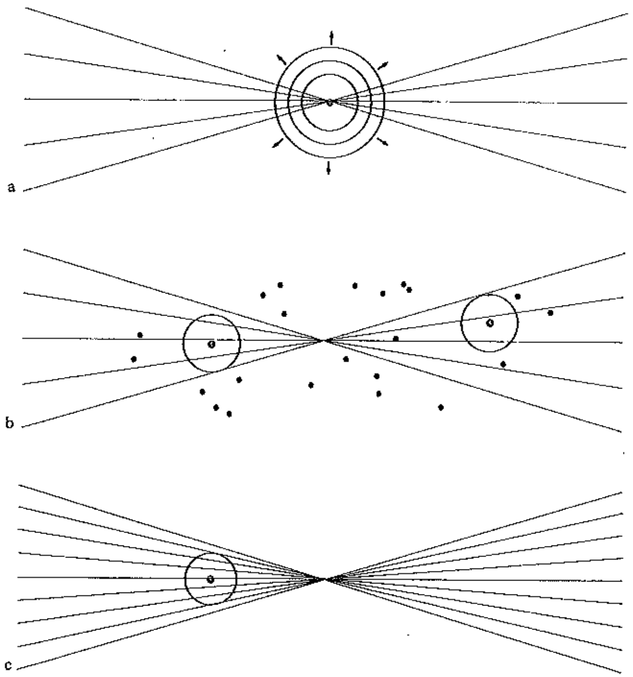

Fig. 2.156. **Optical breakdown**

a If the energy density at the focus reaches the threshold level for inducing ionization, optical breakdown follows. A plasma forms at the focus, and mechanical phenomena spread outward from that point in all directions.

b In an inhomogeneous medium with sites of lower threshold, optical breakdown can occur anywhere within the light beam.

c If energy input is increased, the energy density may reach the threshold level in front of the focus, and prefocal optical breakdown will occur at some point on the axis of the incident beam

which defines the ideal wavelength for localizing the *site of action* to the desired layer. Monochromatic light is used for high-precision work. Polychromatic (white) light, containing a mixture of wavelengths, has different absorption spectra in various tissue layers.

The energy source for **application** of the light may have a linear or nonlinear mode of operation. In **linear** systems, increasing the energy of the light beam also increases its effect.[77] The amount of energy delivered to the tissue is easily controlled by adjusting the spot size and the power density ("intensity") of the light and the exposure time. When visible light is used, *monitoring* of the treatment can be done visually and is therefore simple and precise. Any optical barriers are easily recognized, and the effect is apparent.[78] If the *exposure time* is longer than the surgeon's reaction time, the various parameters can be adjusted as needed while the treatment is carried out.

Nonlinear effects can occur with energy sources whose *power* is increased by greatly compressing the energy in space and time. These sources deliver their power output in *pulses of several nanoseconds* duration or less.[79] There is no linear relationship between energy and response, for the latter is *threshold dependent*, i.e., no response occurs below the threshold, and the light continues to be transmitted past the focus. The response at or above the threshold consists of an explosive *optical breakdown* with associated thermal and mechanical effects (Fig. 2.156a).[80] Thus, nonlinear energy sources are suitable only for tissue division by the removal of material (see Fig. 2.51), provided it is acceptable for the tissue debris to remain within the eye.

Control is far more difficult with nonlinear energy sources than with linear sources, because the operator cannot influence events during the application. Rather, he must predict the effect in advance and adjust the power settings accordingly. This *prognosis* is based on "experience" and cannot be made with absolute confidence. The basic problem is that optical breakdown follows *statistical laws*. This means that the desired response may or may not occur at a given power output (Fig. 2.157). Thus, while the probability of a desired result can be estimated by statistical means, the exact result in a particular energy delivery cannot be predicted. The situation is further complicated by the fact that the threshold for a given clinical situation is unknown. Visible as well as invisible imperfections in the substrate (e.g., contamination by free electrically charged particles, surface irregularities on ocular media) can lower the threshold at some locations, allowing optical breakdown to occur at unanticipated sites anywhere within the beam (Fig. 2.156b). Increasing the energy output likewise can shift the effect away from the focus because energy densities may be produced in front of the focus that are high enough to precipitate optical breakdown (Fig. 2.156c).

So even with an optimum focusing technique, the operator cannot know precisely *when*, *where*, and *how strong* optical breakdown will be at the moment the pulse is emitted. He cannot know, in other words, whether the pulse will produce *no effect*, the *desired effect*, or *over-effect*. The best safety strategy for the use of pulsed lasers involves the maintenance of adequate *clearances*, i.e., performing laser coagulation only at sites where there is an adequate distance between the focus and structures that must be preserved.

Within the limits imposed by this safety strategy, we can set forth **technical and tactical guidelines** for the optimum utilization of nonlinear ophthalmic lasers:

The essential *technical* requirement is sharp focusing, accomplished by:

- eliminating sharpness-degrading "impurities" in the projected beam (having a beam of pure wavelength and mode);

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[77] Examples: Argon laser, crypton laser, Nd:YAG laser in the free-running mode.

[78] For example, coagulated protein is recognized by tissue discoloration, collagen shrinkage by tissue displacement, and over-treatment by the formation of vapor bubbles.

[79] Examples: Q-switched Nd:YAG laser in the nanosecond range, mode-locked Nd:YAG laser in the picosecond range.

[80] The thermal effects are coagulation or vaporization of the tissue. The mechanical effects are tissue destruction by acoustic and shock waves and other physical phenomena. The destructive effects are determined not just by the energy of a single pulse but also by the mode of pulse sequencing, e.g., the temporal emission pattern of pulses of uniform or variable intensity.

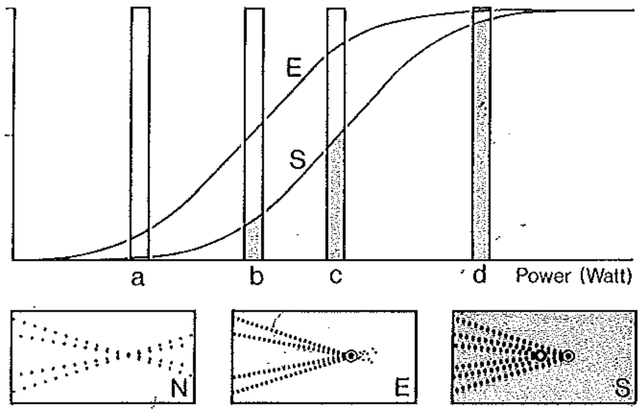

Fig. 2.157. The statistical nature of optical breakdown
N: No-effects: Full transmission of the emitted energy through the focus. There are only variations in energy density along the optical axis.
E: Desired effects: Optical breakdown occurs at the planned site (i.e., at the focus) and at the planned intensity.
S: Side-effects: Extrafocal and oversized breakdowns, causing damage to structures away from the target.
The curve shows the probability (in %) of the events *N*, *E*, and *S* to be expected at a given power output.

a Power below threshold for optical breakdown: While most of the deliveries will not produce optical breakdown, already some desired effects will occur, and rarely even some side-effects.

b Power at threshold for *E*: 50% of the deliveries will be desired effects, but there will be *N* as well, and even the danger of *S* increases.

c Power at threshold for *S*: 50% of the deliveries are side-effects. The majority of the other effects are *E*, but there are still *N*.

d Power above threshold for *S*: Besides *S* there are still some *E* and even *N*!

Note: The thresholds for *E* and *S* are not technically defined quantities but vary for every exposure, that is, at every new target (= new substrate) and after every delivery (= change of substrate). Thresholds, thus, are spatially and temporally unstable.
Practical significance: After observing the result of one delivery (at a given energy) it is impossible to predict the result of the next delivery (at the same energy output)!

increasing beam convergence by use of convex contact lenses (see Fig. 2.155b).

From a *tactical* standpoint, the surgeon should employ methods that allow him to work gradually from a safety zone toward the target – this in terms of energy dosage as well as topography:

- The energy of the beam is low (subthreshold) initially and is gradually raised to the threshold level. Multiple applications are performed at each level due to the statistical nature of the optical breakdown effect.
- The beam is initially projected into a region where breakdown is harmless (safety zone) and from there is gradually moved toward the critical target region.
- Each time the energy level is raised, the beam is redirected toward the safety zone, and the approach maneuver is repeated due to the potential for optical breakdown outside the focus (see Fig. 2.156c).
- Treatment is discontinued when the cellular debris from previous optical breakdowns create nonhomogeneities in the substrate that pose a risk of extrafocal breakdown (Fig. 2.156b). Treatment may be resumed after sufficient time is allowed for spontaneous absorption and elimination of the breakdown products.

2.4 The Utilization of Chemical Effects (Electrolysis)

Direct current flowing between an active and indifferent electrode not only generates heat but also induces a *chemical reaction* involving the dissociation of electrolytes with the release of gas. In the process, alkali radicals incite a *colliquative necrosis* that occurs without significant tissue shrinkage, while acid radicals cause a *coagulation necrosis* with associated tissue shrinkage.

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3 Preparation of the Operating Field

Besides the general surgical goals of asepsis and anesthesia, preparation of the operating field in ophthalmic surgery serves the essential function of *creating optimum space-tactical conditions* for the impending operation.

All measures are directed toward
- *establishing the largest possible margin of deformation* (see Fig. 1.56), and
- *eliminating all factors that reduce or jeopardize this margin of deformation.*

All preparatory measures should be planned with these goals in mind, for they determine the range of options and freedom of manipulations that will be available to the surgeon throughout the operation.

3.1 Lowering the Pressure in the Intraocular Chambers

Preoperative reduction of the intraocular pressure is the essential means for establishing a generous margin of deformation. All other measures are directed toward maintaining this margin of deformation and ensuring that portions of it are not consumed before the operation begins. The general intraocular pressure can be lowered by drugs that decrease aqueous production (e.g., carboanhydrase inhibitors, beta blocking agents) or by measures that reduce the vitreous volume (e.g., osmotically active drugs, mechanical compression of the globe). Only the latter measures can affect the vitreous chamber.

3.2 Anesthesia

There are two ways in which *anesthesia assists spatial tactics* at the start of the operation:

- By *suspending ocular motility*, it eliminates eye movements that might deform the open globe. ✓
- By *reducing myogenic tone*, it increases the passive mobility of the globe. ✓

The anesthesia should be applied by a technique which avoids *external pressure* that might alter the lid or orbital volume.

All current anesthesia techniques accomplish the primary goal of anesthesia – the elimination of pain. However, none satisfies all requirements in terms of spatial tactics,

Table 3.1. Comparison of various anesthetic techniques. The colored squares show where practical techniques satisfy the requirements of an ideal anesthesia

	Insensibility	Akinesia	Effect on passive mobility of the globe		Effect on margin of deformation	
			Increase	Decrease	Danger of decrease during initial phase	during final phase
Ideal anesthesia	+	+	+	–	–	–
Instillation anesthesia	+	–	–	–	–	–
Retrobulbar anesthesia	+	+	+ by relaxation of muscles	+ by infiltration of orbital tissue (dose dependent)	+ by infiltration of orbital tissue (dose dependent)	–
General anesthesia	+	+	+ with muscle relaxation	(+) without relaxation	(+) in case of technical difficulties: (defense, agitation, vomiting)	(+)

and so the selection of an anesthesia technique is always a *compromise* (Table 3.1). If the disadvantages of a particular technique are too objectionable in a given situation, different techniques may be combined for an optimum result.[1]

3.2.1 Instillation Anesthesia

The ocular structures most sensitive to pain are the integument (conjunctiva and cornea) and the anterior uvea (iris and ciliary body). Topical anesthetics such as oxybuprocaine and lidocaine are employed to desensitize the conjunctiva and cornea. Deep-acting anesthetics such as cocaine can provide anesthesia for most intraocular procedures. Instillation anesthetics are adequate for procedures in which unrestricted muscular motility does not compromise the surgical goal.

3.2.2 Injection Anesthesia

Injection anesthesia may be applied as *infiltration anesthesia* or *conduction anesthesia*. Besides eliminating pain, it can paralyze the extraocular muscles and thus prevent ocular and lid movements.

A disadvantage of injection anesthesia is that it increases the *periocular tissue volumes*, whether by the volume of the injected anesthetic or by inadvertent hematoma formation. This jeopardizes the margin of deformation.[2] Thus, the injection technique takes into account not only the anatomy of the target structures (e.g., ciliary ganglion, ocular muscles, palpebral muscles, facial nerve) but also means for avoiding a localized volume increase. Uniform distribution of the injected anesthetic can be enhanced by adding hyaluronidase to the solution.[3]

3.2.3 Akinesia of the Orbicularis Muscle

Temporary paralysis of the orbicularis oculi prevents closure of the lids. **Direct infiltration** of the muscle (Fig. 3.1 C) produces a swelling of the lids that may interfere with the conduct of the operation. **Conduction anesthesia** of the facial nerve does not affect the operative field. *Preauricular akinesia* (Figs. 3.1 A, 3.2 A), requires only a small amount of anesthetic. It blocks all the zygomaticotemporal fibers but may also block the descending branches, causing transient oral paralysis. *Paraorbital akinesia* (Figs. 3.1 B and 3.2 B) infiltrates the nerve over the bony orbital rim. The infiltrated area is larger and should include the fibers supplying the outermost parts of the orbicularis, which are very active in lid closure.

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[1] Examples:
- General anesthesia and local infiltration may be combined to prevent ocular and lid movements during recovery from the general anesthesia.
- Instillation anesthesia can be combined with other techniques in patients with large ocular perforations, where eye contents may be extruded due to straining or coughing during induction of general anesthesia or to an increase in the intraorbital volume during infiltration anesthesia. The preliminary placement of a few temporary sutures under instillation anesthesia will lessen the vulnerability of the globe to the side-effects of the other anesthetic measures.

[2] There is particular danger when anesthetic must be reinjected after the eye has been opened. In this case the margin of deformation can be increased by temporarily closing the wound with sutures before performing the reinjection.

[3] Hyaluronidase promotes diffusion of the anesthetic in the tissue by the depolymerization of interstitial hyaluronic acid; it has no effect on proteins (e.g., capillary walls, sclera, fibrin, clotted blood). The action of hyaluronidase is enhanced by pressure to the injected area (compression, massage).

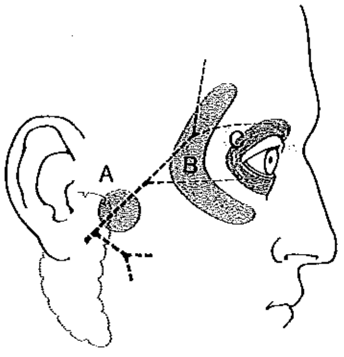

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Fig. 3.1. Methods of producing orbicularis oculi akinesia
A Preauricular conduction anesthesia. *B* Parorbital conduction anesthesia. *C* Direct infiltration of the orbicularis oculi

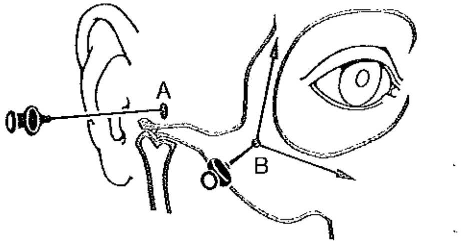


Fig. 3.2. Injection sites for conduction akinesia
A Preauricular injection: About 1 cm^3 is injected anterior to the tragus (i.e., anterior to the mandibular tuberosity, identified by palpation during jaw motion) at a depth of 1 cm.
B Parorbital injection: The needle is inserted over the highest point of the zygomatic arch and is passed upward and nasally along the bony orbital rim. The needle is withdrawn to the tip before it is redirected inferiorly (less traumatizing than "sweeping" the needle through the tissue)

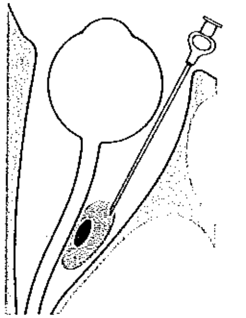


Fig. 3.3. **Retrobulbar infiltration.** To avoid optic nerve injury, the needle is kept in the temporal half of the orbit and should penetrate no farther than 1.5 cm behind the globe

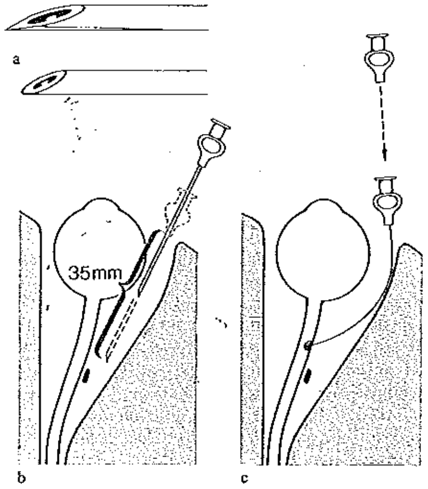


Fig. 3.4. **Requirements of the injection needle**

a *Tip*: A sharp tip (*above*) may cause inadvertent injury, so a tip with lower cutting ability (*below*) is preferred.

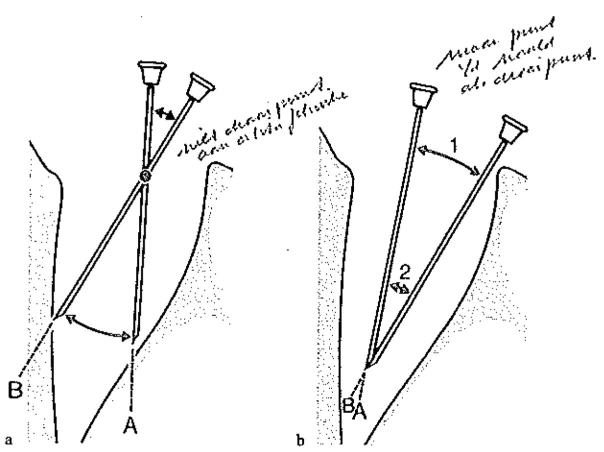
b *Length*: 3.5 cm or less (from the orbital margin) to spare the apex.

c *Rigidity*: While rigid needles are easy to direct with accuracy (as shown in **b**), flexible needles follow the path of least resistance and are more apt to stray. An attempt to correct this by forcibly redirecting the needle may achieve the opposite result (here: redirection to the right causes deviation to the left)

Fig. 3.5. **Guidance motions for intraorbital injection**

a If the needle is pivoted about a fulcrum at the *orbital rim* to redirect it from *A* to *B*, the tip will sweep through the intraorbital tissues and, behaving as a sharp instrument, may cause undetected injury.

✓ **b** If the needle is redirected from *A* to *B* by pivoting it *at its tip*, the tip position remains stable. Instead the needle will displace tissues at the orbital margin (*1*), but there it behaves as a blunt instrument; also, the orbital rim tissues are not as critical as the deep intraorbital tissues. Redirection is even less problematic when the needle is inserted transconjunctivally. In this case the needle enters the orbit farther posteriorly, and the amplitude of tissue shifts during corrective maneuvers is reduced (*2*)



niet draaipunt.
aan de tip stabiele

Meer punt
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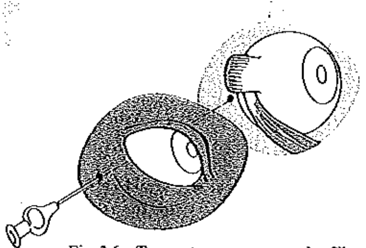

Fig. 3.6. **Transcutaneous approach.** The needle is inserted in the lower temporal quadrant, below the tarsus. Rotating the eye upward and nasally removes the inferior oblique muscle from the needle path and stretches the peribulbar tissue, which is then pierced more easily

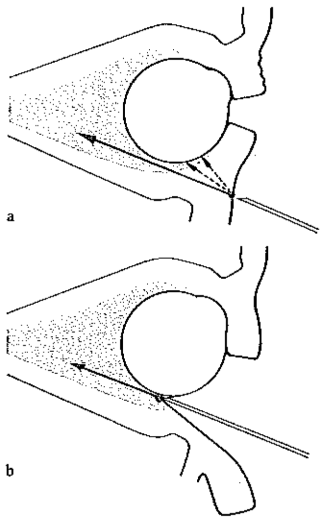

Fig. 3.7. **Comparison of transcutaneous and transconjunctival injection**

a *Transcutaneous injection*: A misdirected needle can perforate the globe (*dashed arrows*). The steeper the angle of insertion and the longer the globe (myopia), the greater the danger.

b *Transconjunctival injection*: The needle is inserted behind the equator and will either miss the globe completely or bypass it at a tangent. The needle enters the muscle cone directly

3.2.4 Retrobulbar Anesthesia

Retrobulbar injection blocks the *ciliary ganglion* and paralyzes the *ocular muscles* by diffusely infiltrating the posterior portions of the muscle cone. The orbital apex is vulnerable, however, because the optic nerve, veins, and other structures are so closely related that they will not yield to an advancing needle and are susceptible to puncture (Fig. 3.3). This danger can be reduced by using *cannulas* of an appropriate shape, length, and rigidity (Fig. 3.4) and by using an appropriate *guidance technique* (Fig. 3.5).

In the **transcutaneous injection** the cannula reaches the muscle cone by piercing the lid, orbital septum, fascia, and orbital fat (Figs. 3.6, 3.7a). It encounters a relatively high, superficial cutaneous resistance that may make it difficult to appreciate the resistance offered by deeper structures.

For **transconjunctival injection** the cannula is inserted at the fornix (Fig. 3.8) and is passed through the periocular fascia *directly into the muscle cone.* The major difference between transcutaneous and transconjunctival injection is that in the latter, the cannula tip is inserted beyond the largest ocular diameter and so is unlikely to perforate the eye (Fig. 3.7b).[4]

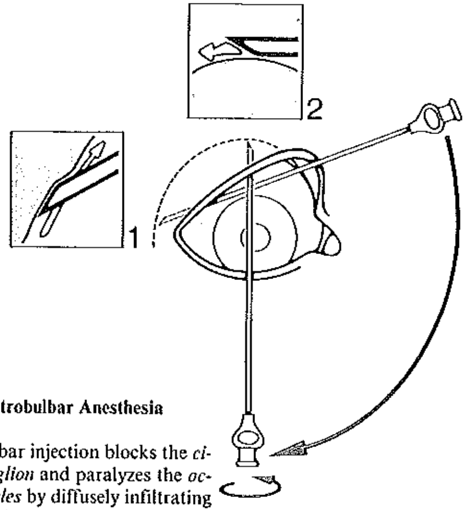

Fig. 3.8. **Technique of transconjunctival injection.** The drawing shows the technique for injection through the superior fornix, where the insertion site is covered by the tarsus of the upper lid. (An analogous technique may be used in the inferior fornix, although this site is more easily accessible.) The transconjunctival injection consists of two phases: maneuvering the needle to the insertion site in the fornix, and advancing the needle to the target in the orbit.

1 The insertion site in the hidden superior fornix is located by applying the needle at a more easily accessible part of the fornix (i.e., the lateral or nasal canthus) and sweeping it upward to the insertion site (*long arrow*) with the blunt side facing the fornix conjunctivae (*inset 1*).

2 At the insertion site the needle is thrust through the conjunctiva and passed along the globe toward the orbital apex. The blunt side of the needle should face the ocular surface to avoid injury (*inset 2*); this is ensured by rotating the needle 90 degree about its own axis upon insertion (*short arrow*)

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[4] When the globe is open (e.g., injection in case of traumatic perforation or reinjection during intraocular surgery), the transconjunctival route is hazardous. Resistance at the insertion site in the fornix can exert traction on the conjunctiva which may be transmitted to the wound margins and cause them to separate. To prevent this, the conjunctiva must be immobilized with a fixating forceps close to the site of injection.

3.3 Maintaining Separation of the Lids

3.3.1 Methods of Opening the Lids

Simple separation of the lids (Fig. 3.9) recapitulates the natural lid-opening movement, and all movements are consistent with the normal function of anatomic structures. However, this method affords limited exposure and does not eliminate lid pressure on the eye.

Lid retraction (Fig. 3.10) is effected by pulling the eyelids away from the globe, resulting in an *unphysiologic deformation of the entire lid region.* Specifically, the lid margins are stretched and tend toward a circular shape. This "*palpebral circle*" (Fig. 3.11) is formed by pulling the upper and lower margins outward and orbitally, and the lateral margin inward and frontally.[5] The level occupied by the palpebral circle when the lid margins are on maximum stretch depends on the resistance of adjacent tissues. In the absence of anatomic obstructions, this level corresponds to the plane between the insertions of both lateral palpebral ligaments at the orbital margin.

The movements associated with lid retraction cause a widespread *shifting of tissue* that can affect the orbital pressure. *Raising* the palpebral circle away from the globe (Fig. 3.12a) relieves pressure on the orbit, while *lowering* the circle toward the globe (Fig. 3.12b) increases the resistance from the orbital cushion, and passive ocular mobility is reduced. Should the globe come in *direct contact* with the margins or lid retractors, it may be deformed directly (with an associated decrease in the margin of deformation).

For these reasons every effort should be made to *raise* the palpebral circle away from the globe. If this does not happen spontaneously by virtue of the orbital anatomy (Fig. 3.13a), active outward traction must be applied during lid retraction (Fig. 3.13b). The distensi-

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[5] In theory both the inner and outer canthi should move inward. But due to the strong fixation of the nasal canthus, only the lateral canthus is mobile.

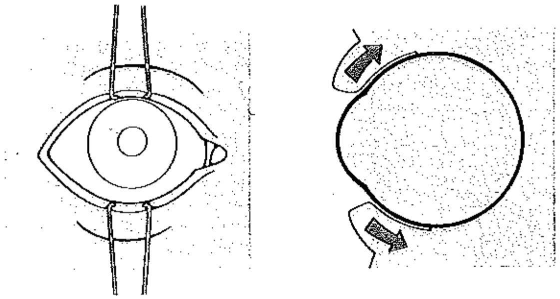


Fig. 3.9. Simple separation of the lids produces a normal palpebral aperture with a normal direction of traction

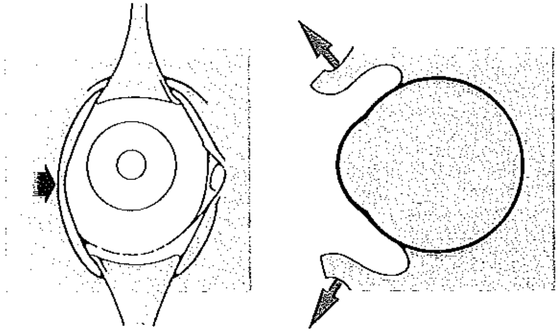


Fig. 3.10. Lid retraction enlarges the palpebral aperture beyond the physiologic width by lifting the eyelids away from the globe

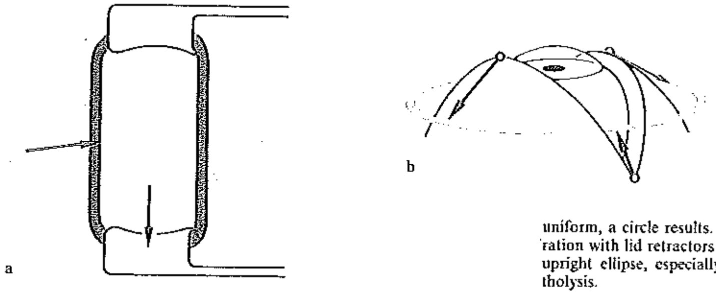


Fig. 3.11. Formation of palpebral circle by stretching of the lid margins. When stretched, the lid margins tend toward a circular shape.

a When the palpebral aperture is increased in the vertical dimension, its transverse diameter is reduced, and the lateral lid margin is pulled inward. If tension is uniform, a circle results. Maximum separation with lid retractors may produce an upright ellipse, especially following cantholysis.

b In an attempt to lie on one plane, the upper and lower lid margins move outward and downward while the lateral margin moves inward and upward

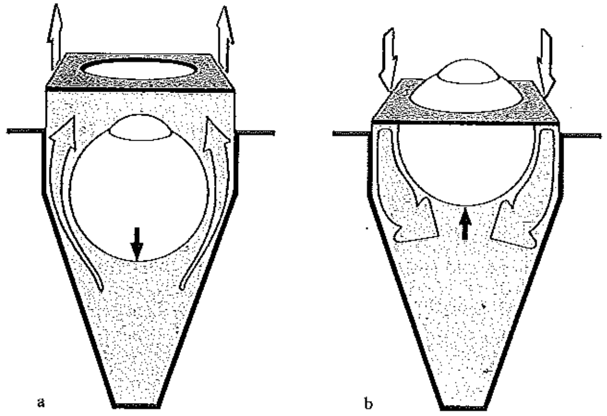


Fig. 3.12. Movement of the palpebral circle in relation to the globe

a When the circle is raised, tissue from the orbital cavity is pulled forward: the globe recedes, the eye muscles relax, and passive mobility of the globe is increased.

b Lowering the circle compresses the orbital tissue: the globe is pressed forward, and passive mobility is decreased

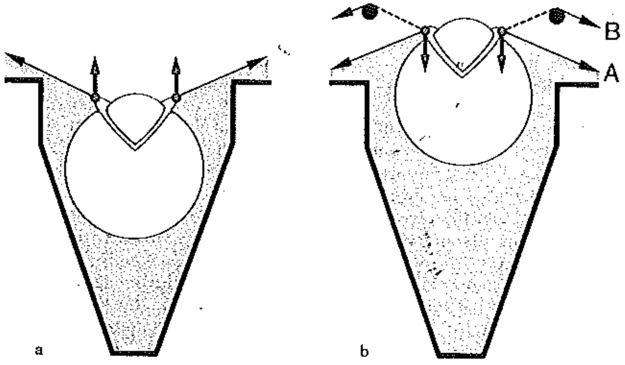


Fig. 3.13. Positioning the palpebral circle. Effect of the direction of lid traction on the position of the palpebral circle.

a If the globe is deeply set, lid traction toward the orbital margin creates outward-directed vectors, and the palpebral circle is raised.

b If the globe is protuberant, lid traction toward the orbital margin (*A*) has an inward-directed component, and the palpebral circle is lowered. To raise the circle, traction must be redirected by means of struts (*B*) to create the situation shown in **a** (*broken line*)

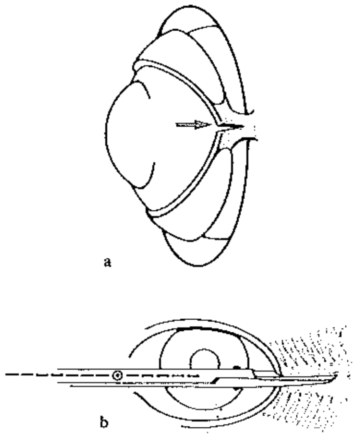


Fig. 3.14. **Canthotomy**

a The incision to enlarge the palpebral circumference causes minimal trauma when made along the lateral muscle raphe.

b This raphe is on the line connecting the inner and outer lid margins and is engaged by applying a straight scissors to the temporal canthus while keeping its handle directly over the nasal canthus. The contiguous tissue layers (skin, fat, muscle, lateral palpebral ligament) are compressed beforehand with a clamp to keep them from shifting during cutting

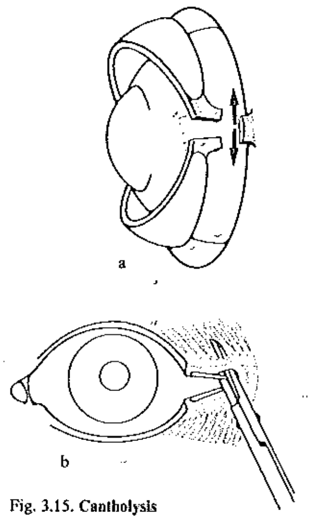


Fig. 3.15. **Cantholysis**

a If a tight lateral ligament prevents elevation of the palpebral circle, its arms are separated from their periosteal attachment.

b The ligamentous attachments are located through the canthotomy incision by probing upward and downward along the inner orbital margin. Cutting directly over the periosteum will help prevent hemorrhage. Traction on the tarsus makes it easier to identify the ligaments and assess the effect of the procedure

bility of the lateral palpebral ligament places an anatomic limit on the level to which the palpebral circle can be raised.

The configuration of the palpebral circle can be surgically altered by **canthotomy** (Fig. 3.14). This increases the palpebral circumference and so relieves direct pressure from the lid margins. **Cantholysis** (Fig. 3.15), or division of the palpebral ligaments, is indicated if these bands prevent the palpebral circle from being raised adequately.

3.3.2 Instruments for Maintaining Lid Separation

Traction sutures (Fig. 3.16) are ideal for effecting and maintaining *lid separation*. If they are used for *lid retraction*, however, difficulties can arise: Because they act only at the lid margins, the sutures have a tendency to evert the tarsus if the globe is recessed, and to lower the palpebral circle if the globe is protuberant (Fig. 3.13). In this case their efficiency can be improved by passing them over special *supports* on the cheek and forehead.

Lid hooks are inserted beneath the lid margin to effect *retraction*. The diameter and level of the palpebral circle can be adjusted as needed with **simple lid hooks** (Fig. 3.17), but these must be handled by an experienced assistant who can deal with special situations as they arise. In the **self-retaining lid retractor** (lid speculum), the hooks for the upper and lower lids are interconnected. If the speculum is of the *spring tension* type, the lid aperture depends entirely on the interaction between the lid tension and spring tension and cannot be adjusted (Fig. 3.18a). If retraction is maintained by a *screw thread* or *screw clamp* mechanism, a specific aperture can be set and adjusted as needed (Fig. 3.18b). The net weight of the instrument determines whether it can travel upward (i.e., outward) with the palpebral circle. Heavy retractors depress the circle and must be elevated away from the bony orbital margin by mechanical supports.

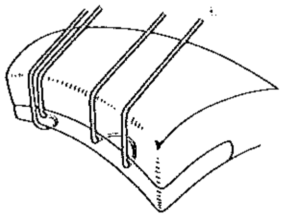


Fig. 3.16. **Traction sutures** are most effective when passed through the tarsus. This anchors them in firm tissue, and there is no danger of hemorrhage from the muscle or marginal artery

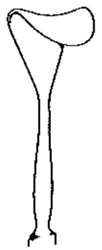
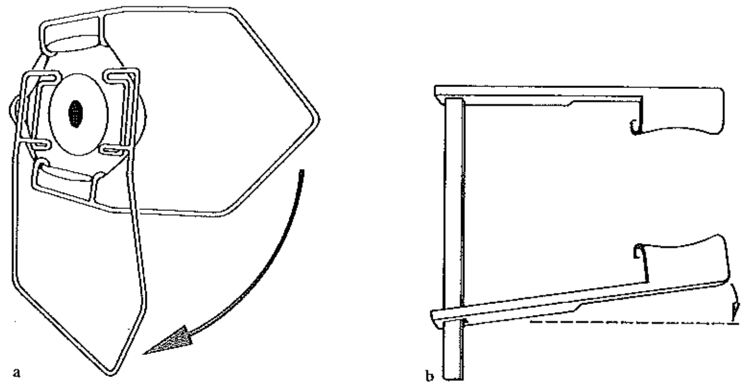


Fig. 3.17. **Simple lid hooks.** The back of the hook conforms to the curvature of the ocular surface at whatever angle it is applied

Fig. 3.18. **Self-retaining lid retractors**

a Light wire speculum with spring tension. For removal, the retractor is rotated 90° (*arrow*), moving the hooks into the horizontal meridian where the palpebral aperture has its largest diameter.

b Lid speculum of the screw-clamp type. For removal, the branches are grasped near the connecting post and are first spread apart slightly (*arrow*) to loosen before they are slid together



3.4 Fixation of the Globe

Since all forces applied to the globe have both a *deforming* and a *displacing* action, the surgeon can increase the resistance to one in order to increase the effect of the other. Increasing the resistance to passive mobility aggravates the risk of deformation, while improving passive mobility reduces the risk of deformation.

Fixation serves to *limit the passive mobility* of the globe so that the intended force vectors of surgical instruments can be optimally applied. However, if *unplanned forces* such as muscular traction act on an immobilized globe, there is a danger of deformation that can be averted only by immediately releasing the fixation so that ocular mobility is restored.

In **point fixation** (Fig. 3.19), passive ocular movements are prevented only if the applied force vectors pass through the center of rotation of the eye and the point of instrument fixation. All vectors from other directions will cause lateral rotation of the globe. Thus, *unplanned forces* tend to displace the globe rather than deform it.

Zonal fixation (Fig. 3.20) immobilizes the eye against vectors from various directions. However, one result of the improved fixation is that unplanned forces[6] now tend to deform the globe rather than displace it.

The **quality of the fixation** depends on the firmness of the *tissue between the fixation instrument and the sclera*. It is best when the globe is grasped directly by the sclera. Fixation by ocular adnexa is most effective when applied close to their site of attachment (i.e., muscles are grasped near their insertion, the conjunctiva near the limbus).

Note: The center of rotation for eye movements is at the ocular center for duction movements with fixation instruments, but rotation takes place about the fixation point for manipulations with operative instruments.[7] As a result, the right and left hand will rotate the globe about different points (Fig. 3.21).

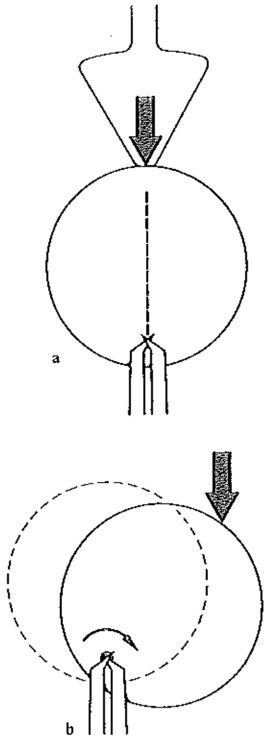


Fig. 3.19. Effect of point fixation

a Point fixation resists only the force vector passing through the center of eye rotation and the fixation site.

b Vectors from other directions *displace* the globe. The center of rotation for this motion is the point at which the fixation instrument is applied

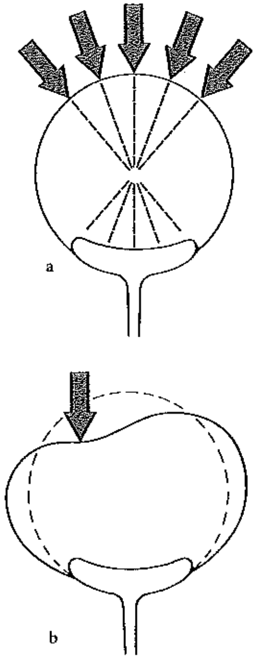


Fig. 3.20. Effect of zonal fixation

a Zonal fixation immobilizes the eye against vectors from various directions.

b Since zonal fixation effectively reduces passive mobility, applied forces *deform* the globe

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[6] Such as resistance to a blunt cutting instrument.

[7] The pattern of resistances may be such that the operating instrument itself (e.g., a blunt cutting instrument) produces a fixation effect, further complicating the rotational movements of the globe.

3.5 Traction Sutures for Orienting the Globe

Traction sutures can be used to rotate a particular part of the globe into the operative field. The extent of the rotation depends on the site of suture placement relative to its fulcrum (Fig. 3.22).

The suture may be attached directly to the sclera or to the adnexa. If the tissue between the suture and the sclera is firm (e.g., attachment to the sclera or a muscle insertion), any traction on the suture will produce a corresponding rotation of the globe. If the intervening tissue is more compliant (e.g., attachment to a tendon or muscle belly), only part of the traction is transmitted to the globe; the eye retains some passive mobility, and this can provide a safety factor in case unplanned forces are applied.

Note: *Immobilization* is *not* the actual purpose of traction sutures. If the suture does exert a fixating effect, it should be released at once if the eye is moved by unplanned forces such as active muscular contraction. Otherwise the globe will be deformed.

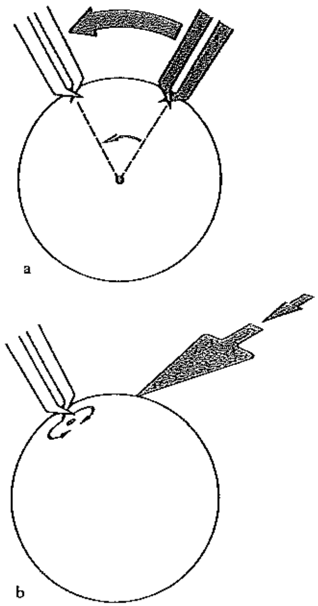

Fig. 3.21. Centers of rotation for passive eye movements

a Intentional rotation of the eye with fixation instruments occurs about the geometric center of the globe (see Fig. 1.44c).

b The fixation instrument forms the center of eye rotation when actions are performed on the globe with other instruments

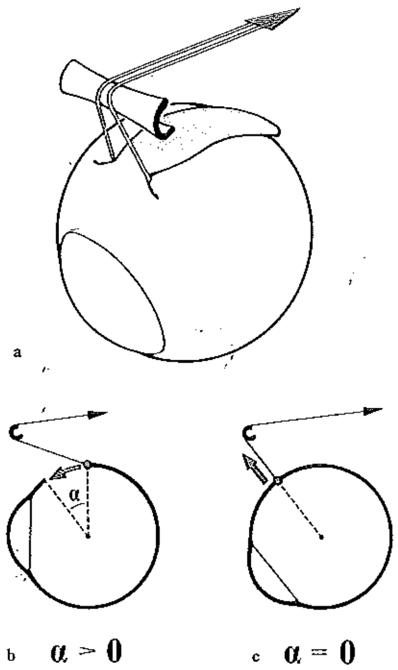

Fig. 3.22. The rotating action of traction sutures ►

a The suture is passed back over the fulcrum formed by the edge of the lid retractor.

b The rotation produced by the suture is determined by the angle α between the line joining the center of rotation with the fulcrum, and the line joining the center of rotation with the point of suture attachment.

c When α=0, rotation ceases. Further traction on the suture only raises (and may deform) the globe

3.6 Sutured-On Stabilizing Rings

Local rings (see Fig. 1.46d) are specially configured to stabilize the *wound margins* for ocular wall excisions and for the accurate fitting of grafts.

Rings for protecting the vitreous chamber (see Fig. 1.47) prevent complications in case of destruction of the *diaphragm*. They are used in situations where there is preexisting damage to the diaphragm, or where a rupture of the diaphragm is anticipated during the course of the operation.

The rings themselves can be a *source of deformation* if attached too tightly (Fig. 3.23), so it is prudent to leave the sutures slightly loose. This will not compromise the function of the ring, since the ring in effect becomes part of the scleral system which itself is not completely rigid.

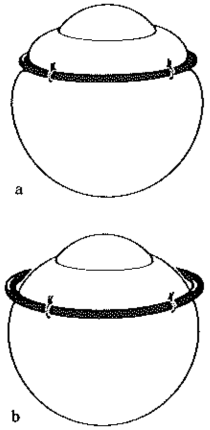

Fig. 3.23. **Sutured-on stabilizing ring**

a If attached too tightly, the ring will deform the globe.

b Even with slightly loose attachment the ring can preserve the anatomy of the diaphragm

3.7 Placement of Transconjunctival Muscle Sutures

If a muscle or tendon must be grasped through the conjunctiva for the purpose of placing a traction suture or stabilizing ring, *statistical data* can be used to estimate the appropriate *distance from the limbus* for the grasping maneuver (Fig. 3.24).

Bleeding is avoided by passing the needle through the *interspace between the muscle and sclera*. This space is defined by *elevating* the muscle away from the sclera. The muscle is grasped through the conjunctiva with a mouse-tooth forceps whose tooth is appropriate for the thickness of the intervening tissue layer (Fig. 3.25). Since the teeth can grasp the tendon only when *perpendicular* to the ocular surface, the intended grasping site must be rotated into view either with a second instrument[8] or with the grasping forceps itself (Fig. 3.27).

On insertion of the needle, inadvertent *perforation* of the sclera is avoided by directing the needle tip strictly parallel to the surface of the globe (Fig. 3.26). Tactile feedback is enhanced by holding the needle stationary and moving the versatile mouse-tooth forceps toward the needle, rather than moving the heavier needleholder toward the fixated muscle.

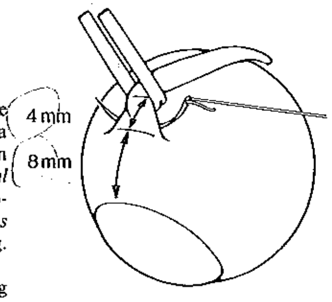

Fig. 3.24. **Transconjunctival muscle suture.** The tendon is grasped far enough behind its insertion that it can be compressed into a bulge. The needle is passed close to the scleral surface

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[8] Examples: Forceps applied at the inferior limbus; squint hook thrust into the lower fornix.

Fig. 3.25. **Grasping through the conjunctiva**

a To grasp the muscle, the forceps blades are opened wider than the muscle width so that the teeth with the included layer of conjunctival tissue can slip beneath the tendon.

b Bringing the blades together causes the tendon to bulge away from the ocular surface

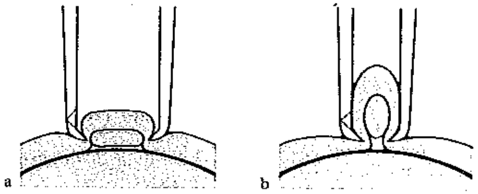
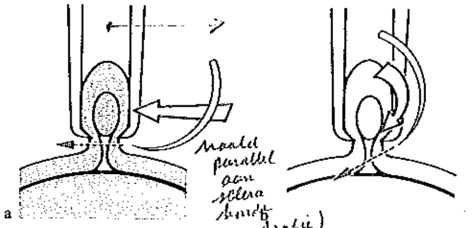


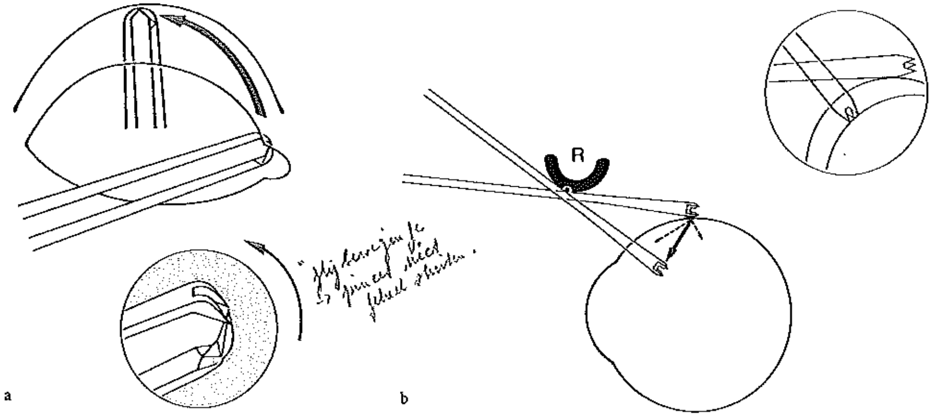
Fig. 3.26. **Passing the muscle suture**

a The needle tip is pushed underneath the tendinous bulge, keeping it parallel to the scleral surface.

b Passing the needle in a rotary motion creates vector components directed toward the sclera, with risk of perforation



naald parallel aan sclera houden (Cave perforatie).



„Hij kan zijn pincet niet geheel sluiten.

Fig. 3.27. **The presentation of tendons covered by the tarsus**

a *Using the forceps to rotate the eye*: The forceps is applied laterally at an accessible part of the fornix and from there is swept upward beneath the lid. *Inset*: Smooth forceps gliding is ensured by closing the blades until the tips just meet (closure is not complete). The two-toothed blade leads, protecting the tissue from the tip of the single-toothed blade.

b To keep the teeth from slipping off the muscle, they are pressed against the eye surface (once in place) by bracing the forceps against the fulcrum of the lid retractor (*R*). The teeth are not closed until they are perpendicular to the eye surface (*inset*), for only then is their grip effective

3.8 Final Check of Preparations

Preparation of the operative field must be undertaken with the greatest care, for errors in this phase jeopardize the conduct of the operation and may be impossible to correct later on.

Before the operation actually begins, a final check is made to confirm that the goals of the preparatory phase have been accomplished:

1. **Efficacy of anesthesia:**
   - elimination of *pain sensation*
   - *akinesia* of the extraocular muscles
2. **Unrestricted passive mobility of the globe:**
   - relaxation of the extraocular muscles
   - no exophthalmus through orbital infiltration or hemorrhage
3. **No direct deformation of the globe.** No contact of globe with lid margins or lid retractor.
4. **Low intraocular pressure.** This is the sign of a large margin of deformation and is the most important preoperative safety criterion.

4 Operations on the Conjunctiva

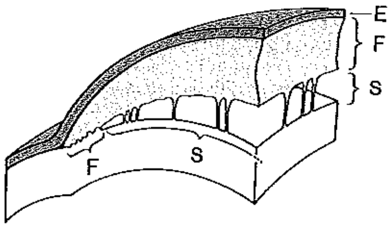


Fig. 4.1. Surgical anatomy of the conjunctiva. *E* The superficial epithelial lamella is continuous with the corneal epithelium. *F* The subepithelial fibrous layer extends as far as the limbus. *S* The episcleral space terminates a short distance from the limbus

4.1 General Problems of Surgical Technique

From a surgical standpoint, the conjunctiva is composed of three layers: the *epithelial layer*, consisting of epithelial cells and a thin supporting layer of connective tissue; a *subepithelial fibrous layer*; and the *episcleral space* (Fig. 4.1).

The **epithelial layer** is closely interwoven with the underlying fibrous layer and presents as a separate layer only when dissected. It is then found to be compliant but of low resiliency, tending to retain any position assumed. The dissected epithelium then also displays its extensive surface area, which is necessary to follow the excursions of the eyeball (Fig. 4.2). Ordinarily the true extent of the epithelium is not apparent due to the constricting effect of the **subepithelial fibers**. Unlike the epithelium, these fibers are resilient and can keep the redundant epithelium from crimping during ocular movements.

Directly adjacent to the globe is the **episcleral space**, which contains a network of fibers loosely connected to the sclera. This space allows for motion of the conjunctiva relative to the scleral surface. About 1–2 mm from the corneal margin the episcleral space terminates at the *perilimbal zone*, where the conjunctiva is connected directly and firmly to the sclera (Fig. 4.3).

With regard to *surgical technique*, it is useful to distinguish *mobile zones* where the conjunctiva is freely movable from *fixation zones* where the conjunctiva is firmly adherent to the sclera (e.g., at the limbus or at scars). Because the tissue can evade cutting edges in the mo-

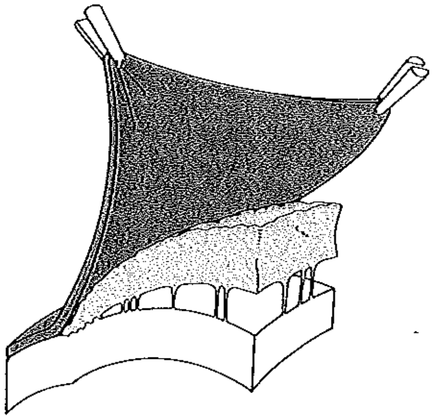


Fig. 4.2. Separating the epithelial lamella from the subepithelial fibrous layer (dissection of large sliding flaps). When dissected from the contractile fibrous layer, the epithelial lamella can be expanded to its full size

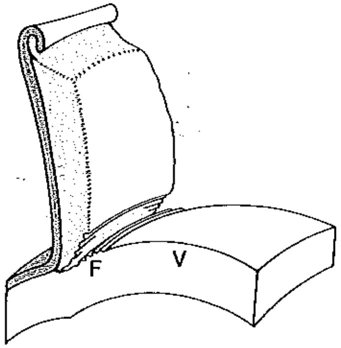


Fig. 4.3. Separating the subepithelial fibrous layer from the sclera (exposure of the globe surface). After the loose connective fibers in the episcleral space (*V*) are detached and the perilimbal fibrous zone (*F*) is divided, the conjunctiva can be elevated to expose the sclera. The conjunctival flap may contract according to the elasticity of the subepithelial fibers

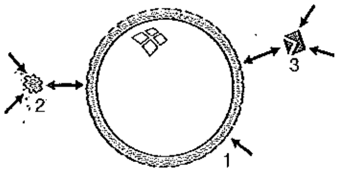


Fig. 4.4. **Shifting tendencies of conjunctival tissue.** During cutting, free conjunctiva shows a lateral shifting tendency like that of tissue fixed on one side (see Fig. 2.63). Thus, it shifts toward the fixation zone at the limbus (*1*), toward scars (*2*), and toward fixating instruments (*3*) (i.e., the resulting incision deviates from those fixation sites). Conjunctiva between two fixation zones shows a forward shifting tendency like that of tissue with bilateral fixation (see Fig. 2.62)

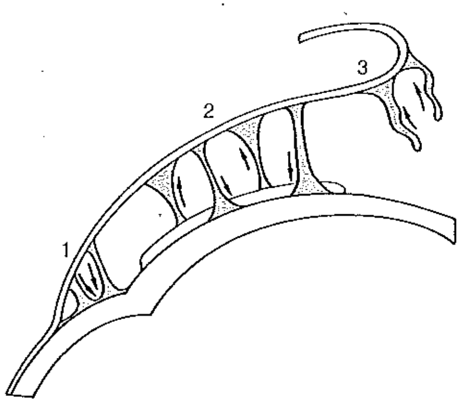


Fig. 4.5. **Shifting tendencies of the subepithelial fibers.** Fibers in the perilimbal zone (*1*) have a stronger attachment to the sclera than to the epithelial lamella, so they tend to shift toward the sclera in front of the blade. In the epibulbar region (*2*) fixation in either area may predominate, so the shifting tendency may be either toward the surface or toward the sclera. As the fornix is approached (*3*), the fibers lose their deep anatomic fixation and tend to shift away from the globe when exposed to a cutting edge

ble zones, its *sectility* is *low*, and it is difficult to dissect these zones with much precision. On the other hand, the low sectility is an important safety factor in that it protects the delicate conjunctival tissue from inadvertent injury. This protection is lacking in **fixation zones**. The closer manipulations are carried to these sites, the greater the danger of inadvertent injury, and the greater the caution that must be exercised when performing the manipulations.

In conjunctival **incisions** the shape and position of the cut are determined by the *shifting tendencies of compliant, resilient tissue* described earlier (see Figs. 2.62–2.64). The *direction* of the incision line (in cuts made perpendicular to the tissue surface) is affected by the *fixation zones at the limbus*, at *scars*, and at *immobilizing instruments* (Fig. 4.4). A cutting edge tends to push the tissue in the direction of these fixation zones, and the resulting incision progressively deviates away from the zones.

Fixation zones that affect the *depth* of the dissected layer (in dissections parallel to the tissue surface) are sites where the subepithelial fibers attach to the epithelium and to the sclera. The stronger fixation at a given location determines the *direction in which the cut tends to deviate*. Thus, the scleral attachment is stronger in the region of the *perilimbal zone*, so the cut tends to deviate toward the surface (Fig. 4.5–1). A downward deviation tends to occur over the *episcleral space*, where the fiber attachment to the globe is so tenuous that the epithelial fixation predominates. This tendency becomes more pronounced toward the *fornix*, where there is no deep fixation at all (Fig. 4.5–3).

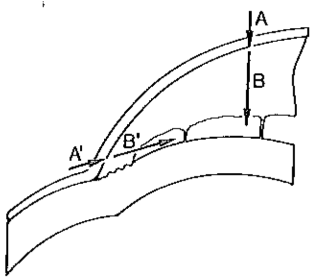
When the conjunctiva is **grasped** and stretched with a forceps, the tissue is both *deformed* and *displaced*. If it is incised in this condition, the incision will acquire a different shape and position when the tissue is released (see Fig. 2.64). Thus, the special properties of compliant, resilient tissue must be taken into account in grasping as well as cutting.

Dissection of the conjunctiva may be performed on a superficial or deep plane. In *superficial dissection* the epithelium is separated from the resilient subepithelial tissue. This yields large *sliding flaps* (Fig. 4.2) that can be used to repair defects in the conjunctiva or superficial corneal layers (epithelial transposition). *Deep dissection* exposes the episcleral space and gives *access* to the sclera, the adnexa, and the interior of the eye (Fig. 4.3). The desired plane is approached *from the limbus* to obtain fornix-based flaps or from the *epibulbar zone* to obtain limbus-based flaps (Figs. 4.6–4.8).

4.2 Episcleral Dissection ("Deep Dissection")

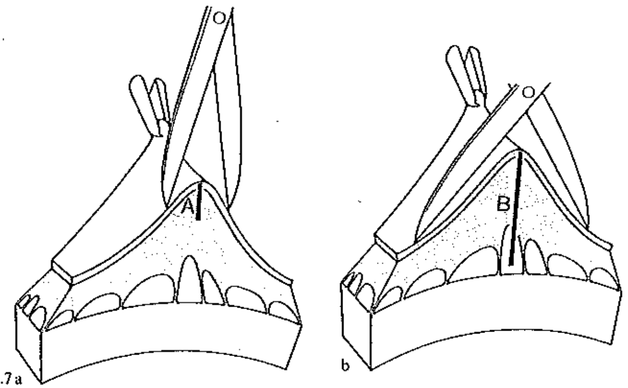
The episcleral space behaves as a *potential space*, which differs markedly from the over- and underlying layers in its loose consistency and so is readily accessible to *blunt* dissection. It can even be defined by fluid injection, and this provides a simple means of identifying the space in confusing situations (e.g., when the anatomy is obscured by scars) (Fig. 4.17b).

A **fornix-based** flap is developed by incising the conjunctiva at the limbus, defining the episcleral space, and undermining the flap toward the fornix. If an attempt is made to cut *from the cornea* in a centrifugal direction (Fig. 4.8), superficial deviation of the incision will tend to occur along the fibers in the firm perilimbal zone, and entry into the episcleral space may prove difficult. Access is made easier by preliminary infiltration of the episcleral



4.6

Fig. 4.6. **Approaches to the deeper tissue layers.** Over the sclera, the conjunctival layers are incised perpendicular to the globe (*A*; *B*). In the approach from the limbus, the desired depth is reached by dissecting parallel to the sclera (*A'*, *B'*)



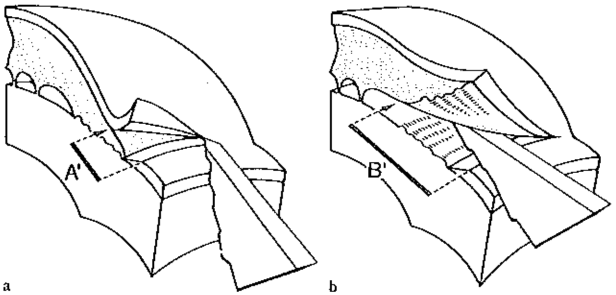
4.7 a

b

Fig. 4.7. **Incising the conjunctiva from its surface.** The placement of the blade tips determines the depth of the incision.

a If only the most superficial layer is to be divided, the tips are placed close to the apex of the fold.

b Placing the tips farther from the apex yields a deeper incision that may enter the episcleral space (*A*, *B*, see Fig. 4.6)



4.8 a

b

Fig. 4.8. **Incising the conjunctiva from the limbus.** The distance of the blade tip from the limbus determines the depth of the incision.

a If the blade tip is passed close to the limbus, only subepithelial fibers are cut.

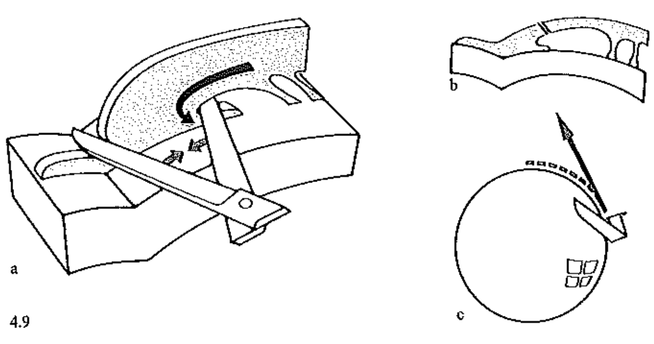
b If the tip is more than 2–3 mm from the limbus, the episcleral space is entered (*A'*, *B'*, see Fig. 4.6)

Fig. 4.9. Effects of lateral shifting tendency in the dissection of a fornix-based conjunctival flap

a One scissor blade is over the cornea, the other has been passed into the episcleral space through an incision. On closure of the scissors, the loose conjunctival tissue shifts across the cutting edge of the blade toward the perilimbal fixation zone.

b This causes a rim of conjunctival tissue to be left on the limbus upon completion of the cut.

c The cut tends to deviate from the limbus progressively, so the rim becomes wider as the cut proceeds. *Broken line*: planned direction of cut. *Arrow*: actual direction of cut



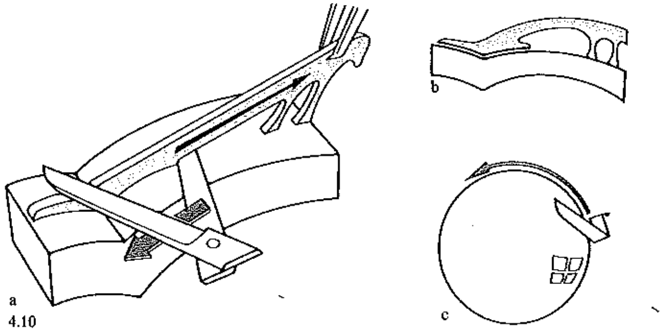
4.9

Fig. 4.10. Prevention of lateral shifting in the dissection of a fornix-based conjunctival flap

a The conjunctiva is pulled away from the limbus by strong forceps traction, while the scissor blade is pushed in the opposite direction when the cut is made. This exploits the retractile tendency described in Fig. 2.64.

b The combination of traction and countertraction allows division of the conjunctiva flush with its limbal attachment.

c With lateral shifting neutralized, the cut follows the intended path along the limbus



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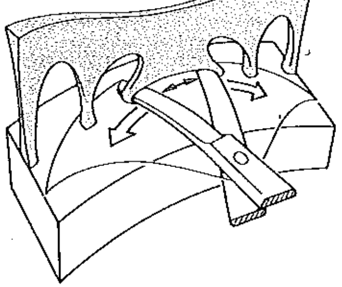
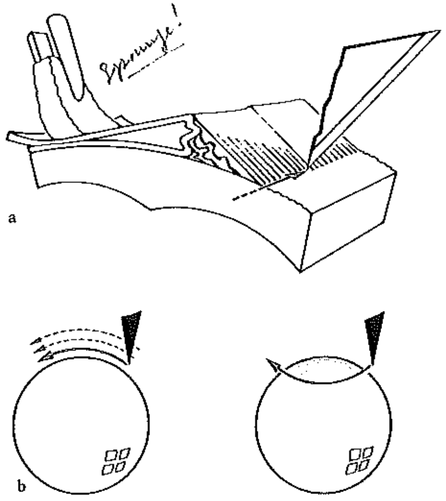


Fig. 4.11. Blunt dissection of the episcleral tissue. The ends of the blades are pressed firmly against the sclera. They contact the fibers to be dissected near their point of attachment, where they are most sectile. The guidance path of the blades follows the ocular surface to preserve the adnexa and orbital tissues

Fig. 4.12. Dissection of a limbus-based flap in the fibrous perilimbal zone with a pointed blade

a Shifting tendencies are minimized by making the perilimbal subepithelial fibers tense. Pressing the reflected flap down onto the cornea creates selective sectility, i.e., only the row of fibers directly in front of the blade is made tense. The adjacent fibers and the epithelial lamella attached to them are in a lax condition and so are less vulnerable (see also Fig. 2.55c).

b Avoidance of hazardous vectors during blade guidance. *Left:* Each cut is made parallel to the limbus to avoid vector components directed toward the cornea. *Right:* There is a tendency to curve the incision in the opposite direction when the surgeon is resting his hand comfortably on a support (i.e., movements tend to occur as a rotation about the support). In this case there are vector components directed toward the cornea, and there is a risk of inadvertent perforation of the conjunctival flap at its base



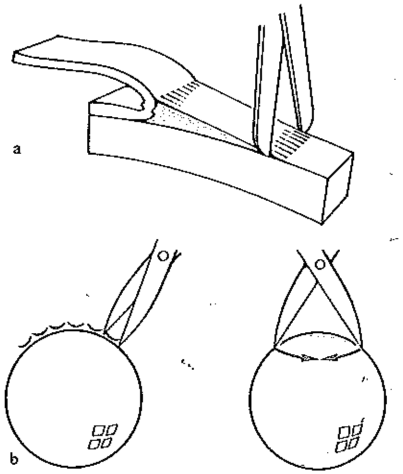
Упруго!

4.12

Fig. 4.13. Scissor dissection of a limbus-based flap in the perilimbal zone

a When the flap is reflected the taut subepithelial fibers closely overlie the sclera, so the scissor points can divide them only when the blades are held vertically (see Fig. 2.85).

b Avoidance of hazardous vectors. *Left*: On closure from a small blade aperture, the tips of the scissors are guided almost parallel to the limbus. *Right*: On closure from a large aperture, the tips move in the direction of the reflected conjunctival flap and may perforate it



4.13

space with fluid; this will also inhibit shifting of the perilimbal fibers when the incision is made.

The easiest method of dissecting the perilimbal zone is to open the episcleral space with a *small radial incision*, insert one blade of a scissors into the space through the incision, and then continue the cut on a path parallel to the limbus. The shifting tendency of the tissue will tend to deflect the cut toward the mobile zone (see Fig. 4.9), but this can be prevented by exerting firm traction on the conjunctiva, pulling it away from its fixation site at the limbus (Fig. 4.10).

Once the episcleral space has been entered, the sclera can be satisfactorily exposed by *blunt dissection*. The surgeon should keep the scissors blades continuously in *contact with the sclera* and pressed firmly against its surface (Fig. 4.11), especially if visibility is poor and he must rely on tactile feedback. This ensures that the dissection will indeed follow the scleral surface while sparing other structures inside the orbit.[1]

A **limbus-based flap** is developed by opening the conjunctiva over the episcleral space and dissecting from there toward the limbus. The incision starts in the easily dissected potential space and terminates at the fixation zone. At that site manipulations must be performed with greater precision, especially if the perilimbal zone is to be mobilized as far as the corneal epithelium. Tissue sectility in that area is high, and the layer to be dissected is thin and fragile, so there is a correspondingly greater risk of inadvertent flap perforation. This is avoided by guiding the blades strictly *parallel to the limbus*, as this eliminates vector components directed toward the cornea (Figs. 4.12, 4.13). Even so, there is a danger of perforation if the *lateral shifting tendency* of the tissue draws the conjunctival flap into the path

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[1] This is particularly important in dissections behind the ocular equator (e.g., for enucleations or procedures at the insertion of the musculus obliquus inferior). Unless the scissors blades stay in contact with the sclera, they will stray into the orbit, and separation of the blades can inflict damage within the close confines of the orbital cone.

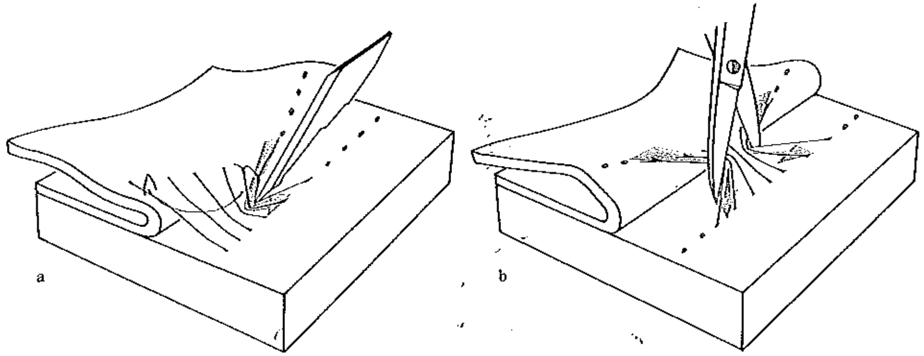

Fig. 4.14. **Effect of lateral shifting tendency during dissection at the limbus.** A blade directed parallel to the limbus pushes fibers from the reflected flap toward their scleral attachment. The greater the distance traveled by the blade, the more tissue is shifted scleralward. Ultimately the conjunctival surface may enter the cutting path and become sectioned.

a Lateral shifting tendency when cutting with a razor blade tip.

b Shifting tendency when cutting with scissors. Tissue is drawn between the blades during closure. Since the amount of shift (and the danger of flap perforation) depends on the distance traveled by the cutting point, it varies with the blade aperture and can be reduced by taking small scissor bites (see also Fig. 4.13 b)

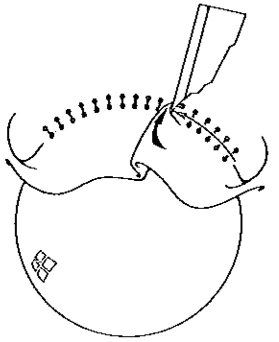

Fig. 4.15. **Signs of impending perforation during lateral shifting of the conjunctival flap.** Tissue folds crossing the limbus are a sign that there are still undivided fibers in front of the blade. These fibers pull the conjunctival flap toward its site of scleral attachment and may draw the epithelial lamella into the path of the blade. *Note*: The presence of these folds indicates that the countertension on the flap is insufficient to neutralize the shifting tendency. The remedy is increased countertraction on the flap (as illustrated in Fig. 4.12a).

In the drawing the *white* portion of the perilimbal zone (to the *right* of the fold) represents the part already divided; the *gray* portion (*left*) is not yet divided

of the blade (Figs. 4.14, 4.15). This is avoided by applying *countertraction* on the flap in the direction of the cornea.

When all the subepithelial fibers have been divided as far as the limbus, the fold at the reflected epithelial layer appears as a *sharp step*, signifying that the episcleral dissection is complete and any further cuts would perforate the flap itself (Fig. 4.16).

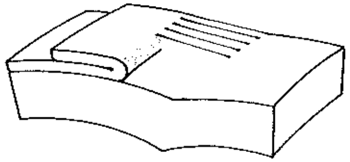

Fig. 4.16. **The completion of deep episcleral dissection.** When the last subepithelial fiber attachments have been severed, a conspicuous step (*gray*) appears at the reflection of the epithelial lamella. Where fibers are still present, the flap surface appears to be continuous with the sclera

4.3 Subepithelial Dissection ("Superficial Dissection")

Superficial dissection separates the conjunctival epithelium from the resilient subepithelial fibrous layer. It is technically more demanding than episcleral dissection, because it does not follow a preexisting space. The surgeon himself must *define the plane of the dissection.*

The *size and mobility* of superficial conjunctival flaps depend on how carefully the contractile subepithelial fibers have been divided, i.e., how thinly the flap has been developed.[2] This is made difficult by the poor sectility of the subepithelial fibers. The fibers may shift upward or downward ahead of the blade, depending on the predominance of the fixation sites, resulting in a corresponding deviation of the cut. The surgeon's task is to apply measures that will *increase the sectility* of the subepithelial fibers while influencing the *shifting tendencies* in a way that will allow the dissection to proceed on the desired plane.

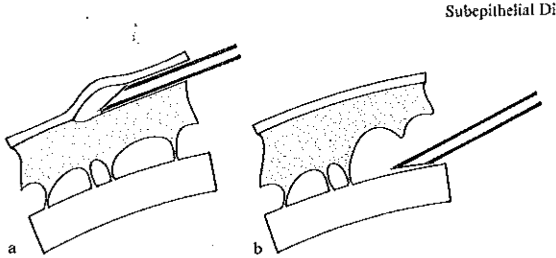
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Fig. 4.17. **Fluid infiltration of the conjunctiva**

a Superficial infiltration of the subepithelial fibers. The cannula is inserted just below the conjunctival surface, its blunt side facing upward to avoid epithelial injury. Superficial infiltration increases the tension of the subepithelial fibers.

b Deep infiltration of the episcleral space. The cannula glides smoothly over the sclera with its blunt side turned downward. Infiltration of the episcleral space reduces tension on the subepithelial fibers

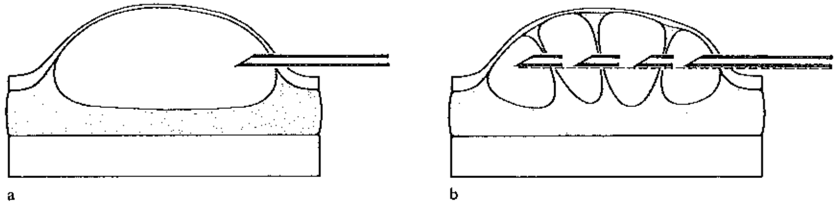
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Fig. 4.18. **Technique of subepithelial infiltration**

a Dissection with fluid: Injecting fluid from a stationary cannula forms a large vesicle which disrupts the finer subepithelial fibers and creates a cavity. When incised, the whole vesicle collapses and cannot maintain tension during the dissection.

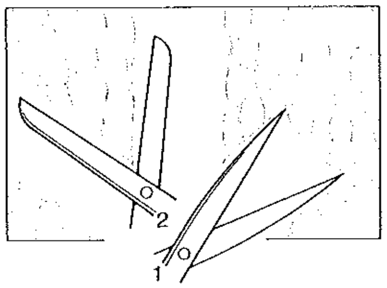
b Increasing tension with fluid: If the cannula is advanced during the injection, numerous small fluid chambers are formed which provide tension even during progressive superficial dissection

General sectility can be increased by *infiltrating the tissue with fluid* (Figs. 4.17a, 4.18), and employing a special dissection technique to avoid premature drainage of this fluid (Fig. 4.19).

Local sectility can be enhanced by making the fibers tense with forceps or with the *scissors* itself (Fig. 4.20). This tension can be produced only if the fibers are *firmly anchored to the sclera.* If this fixation is absent, the fibers will shift toward the epithelium, and a thin flap cannot be dissected. Even exerting greater upward traction will not offset this tendency and would only draw more fibers toward the epithelium, resulting in an even thicker flap (Fig. 4.21).

The surgeon's main task in superficial dissection, then, is to *preserve* existing *deep attachments* and to *create* them where they do not already exist. Above all, he must avoid opening the episcleral space either by cutting (Fig. 4.21 *left*) or by fluid infiltration (Fig. 4.17b). In the region close to the *fornix*, where the conjunctiva lacks a deep anatomic fixation, this fixation must be created artificially by *traction to the subepithelial fibers* (e.g., with traction sutures, Fig. 4.22). This traction simultaneously *redirects* the

Fig. 4.19. **Dissection of the infiltrated conjunctiva.** Tension is maintained in the infiltrated region as long as possible by first cutting discrete channels through the infiltrated tissue (*1*), leaving "pillars" in between to preserve tension. These pillars are then divided in a second step (*2*)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[2] The subepithelial dissection of a sliding flap for whole-cornea coverage is especially challenging. A very thin flap is needed not just to obtain a tension-free flap of adequate size but also for cosmetic reasons, since the flap should be as transparent as possible.

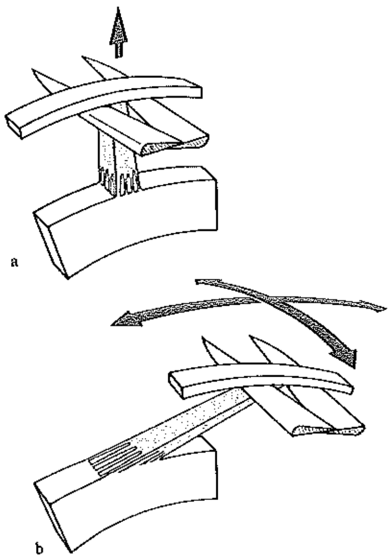


Fig. 4.20. Stretching the subepithelial fibers with scissors

a Stretching the fibers by lifting the fibers vertically from the globe.

b If the tension produced by this maneuver is insufficient, it can be increased by adding a lateral motion of the scissors

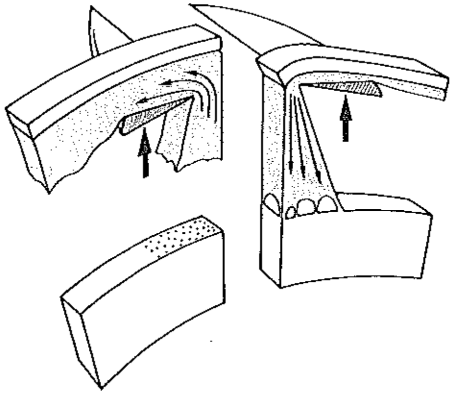
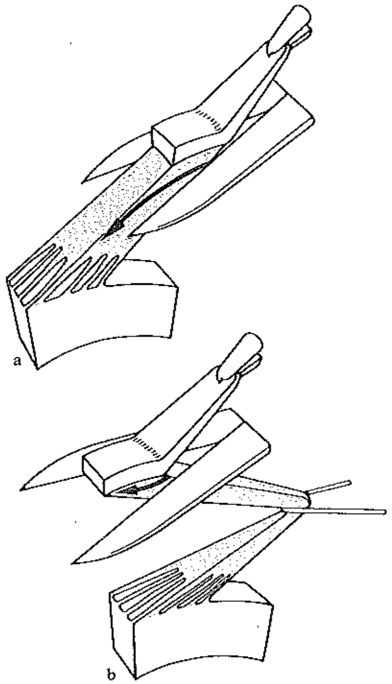


Fig. 4.21. Lateral shifting tendency as an aid to conjunctival dissection. When stretched, the fibers ahead of the advancing blade are shifted in the direction of the strongest fixation. *Right*: Fibers securely attached to the sclera are shifted toward that attachment. Exerting more tension accentuates this effect, yielding a thinner superficial layer. *Left*: In the absence of scleral attachments, the epithelial lamella becomes the strongest fixation site, and the subepithelial fibers are shifted toward it by the advancing blade. This results in a thick dissected layer, which becomes even thicker as more upward tension is applied



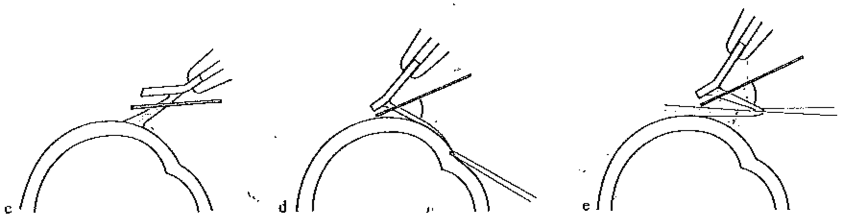


Fig. 4.22. Inverting the angle of attack of the cutting point. The subepithelial fibers cause a lamellar deflection of the cutting point when under tension. The angle of attack determines the direction of the deflection.

a If the subepithelial fibers *above* the scissors are pulled toward the scissor joint by traction on the epithelial lamella, they present to the cutting point in a manner that deflects the cut downward (toward the sclera), and the dissected superficial layer contains more subepithelial fibers.

b If the subepithelial fibers *below* the scissors are pulled toward the scissors joint, the angle of attack is inverted, the cutting point is driven upward, and a thinner lamella is obtained.

c–e Angle of attack of the scissors on the subepithelial fibers. The *red line* indicates the path of the cutting point.

c Traction on the *superficial lamella* presents the subepithelial fibers in a way that deflects the cut downward (analogous to **a**).

d Inverting the attack angle: At sites where the subepithelial fibers are well anchored to the sclera, a traction suture *in the globe* can present the fibers at an angle that deflects the cut toward the surface.

e Inverting the attack angle: At sites where the subepithelial fibers lack adequate deep fixation, the angle is inverted by a traction suture placed *through the fibers themselves* (analogous to **b**)

subepithelial fibers, producing a lamellar deflection which drives the cutting point of the scissors toward the epithelium and helps to keep the dissection on a superficial plane.

The deep fixation can produce an **infolding effect** when the flap is *elevated*. These infolds, which can lead to inadvertent perforation of the thin flap (Fig. 4.23), are avoided by applying a *skillful blend of tension and countertension* and by continually adjusting to the changing conditions. Perforations can also be avoided by cutting with a *small scissors aperture* so that the folds are not drawn into the interblade area.

Superficial and deep flap dissection employ different techniques of *scissor guidance* in that a large blade aperture is generally used for deep dissection and a small aperture for superficial dissection. Also, whereas blunt scissors may be used for deep dissection, superficial dissection requires sharp scissors with pointed tips that can cut effectively in small "bites" (see Fig. 2.84a).

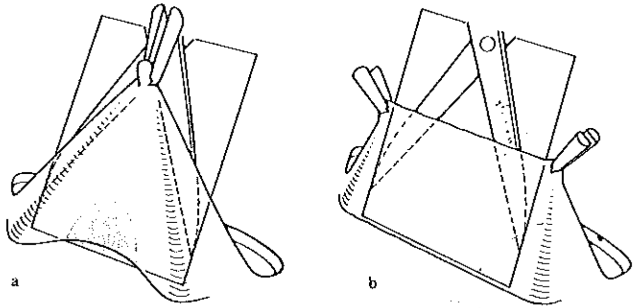


Fig. 4.23. **Deformation of the conjunctiva by local traction to the subepithelial fibers**

a On elevation of the conjunctiva, the still-adherent subepithelial fibers produce a deep infold that may come between the scissor blades leading to perforation of the epithelial lamella. This is avoided by taking very small scissor bites, i.e., working with a small interblade area.

b If the conjunctiva is stretched out flat so that it parallels the guidance path of the scissors, the scissors can cut close along the surface without perforating it. The guidance path of the scissors (i.e., the surface on which the cutting edges move during closure) is outlined in *red*

4.4 Suturing the Conjunctiva

The margins of conjunctival wounds have a tendency to curl due to the resiliency of the subepithelial fibers. To obtain proper apposition of the layers for suturing, this *retraction* must be offset by *countertraction* on the subepithelial fibers. The fibers are engaged with the tooth of one forceps tip or grasped directly with a small forceps and stretched out. This expands the overlying epithelial layer, which can then be pierced at its margin (recognized by its distinctive vascular pattern) with a suture needle.

The inherent compliance of the conjunctiva allows great latitude in the selection of suturing techniques. Tissue deformations by the suture rarely compromise the operative goal. They can even be utilized to effect the compression necessary for uniting the tissues.

The postoperative adherence of the conjunctiva is extremely good and rapid on a vascular substrate but is poor on the avascular corneal surface. Hence, **conjunctival flaps** for covering the cornea should be fixed to the vascularized circumcorneal tissue. Flaps for *partial corneal coverage* can be advanced onto the cornea and made tense by shortening the wound margins with sutures (Figs. 4.24, 4.25), but this tension cannot withstand strong disruptive forces. To counteract high pressures, epicorneal sutures are used to secure the flap (Figs. 4.26, 4.27).

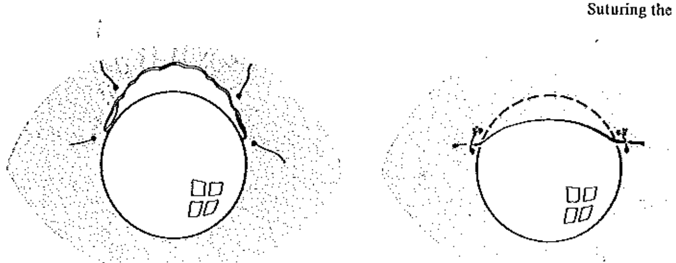


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Fig. 4.24. **Fixation of a conjunctival flap by plicating the lateral wound margins.** The lateral wound margins are plicated with sutures and fixed episclerally. This exerts tension on the flap and presses it onto the cornea. The tension achieved depends on the number of contractile subepithelial fibers still adherent. But this also increases the retractile tendency of the flap, causing it gradually to recede

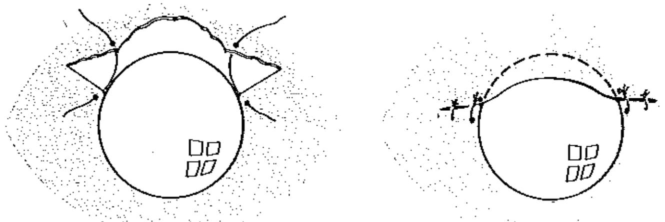

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Fig. 4.25. **Fixation of a conjunctival flap by lateral wedge excisions.** Redundant conjunctiva at the lateral wound edges is excised, and the margins are approximated with sutures. This eliminates the bulging effect in the preceding figure and promotes rapid adhesion

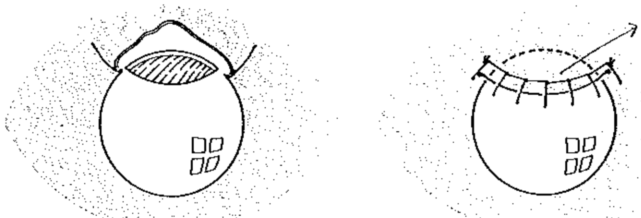

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Fig. 4.26. **Fixation of a conjunctival flap over a small lamellar keratectomy.** The conjunctival flap is tacked to the cornea with a watertight lock-stitch suture. The curvature of the wound line controls the position of the linking thread segments, so that they overlie the conjunctival side of the suture (see Fig. 2.117)

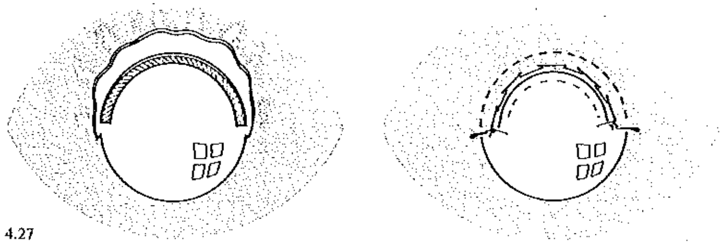

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Fig. 4.27. **Fixation of a flap over a large lamellar keratectomy parallel to the limbus.** The flap is secured with an inverted meandering suture, whose bridging segments keep the flap pressed firmly onto the cornea. (With a lock-stitch suture, the bridging segments would slip off the flap because the curvature is opposite to that in Fig. 4.26)

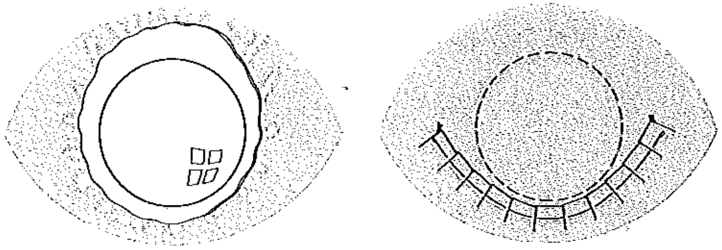

Fig. 4.28. **Fixation of a conjunctival flap covering the whole-cornea.** The thin, delicate flap is tacked to the sclera with a lock stitch. The curve of the suture line keeps the linking segments in the correct position for compressing the flap onto the limbus (cf. Fig. 4.26)

Flaps for total corneal coverage are advanced over the cornea and sutured to the vascularized limbal sclera on the opposite side. Flaps of this size are very thin and can tolerate little tension at the wound margin, so suture types are chosen that exert pressure over a large area (Fig. 4.28).

In electrocoaptation the conjunctiva is squeezed into a fold between the blades of a *bipolar forceps* (Fig. 4.29) and then coagulated. The coagulum forming between the electrodes is comparable to a fast-setting adhesive. Though unable to resist strong forces, electrocoaptation is appropriate for the fixation of conjunctival flaps that are placed without tension and adhere rapidly to the substrate.

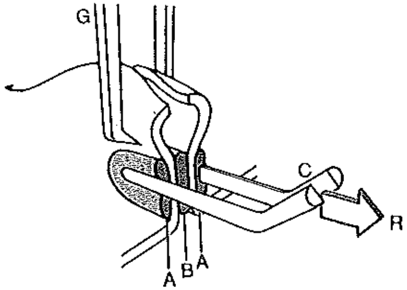

Fig. 4.29. **Electrocoaptation of the conjunctiva.** *G* Grasping forceps for approximating the conjunctiva. *C*, Bipolar diathermy coapting forceps. The diathermy effect bonds the conjunctival fold (see Fig. 4.24) together by coagulated protein (*B*). But similar coagula can form between the conjunctival surface and coagulating forceps (*A*). If the adhesions at *A* are stronger than the adhesion at *B*, the latter (which is the goal of the manipulation) may separate when the coapting forceps are opened. This is avoided by keeping the coapting forceps closed while withdrawing it along the fold (*arrow R*). Additionally, the grasping forceps *G* holding the conjunctival fold together is removed only after the coapting forceps *C* has released the tissue

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5 Operations on the Cornea and Sclera

5.1 General Problems of Surgical Technique

The coats of the eye consist of lamellar tissue. From a surgical standpoint we may distinguish zones with very *regular lamellae*, such as the cornea, from zones with *irregular lamellae*, such as the sclera. These zones differ optically in their transparency, and their anatomic junction occurs in the bluish-gray transition zone at the limbus (Fig. 5.1).

The technique of surgical manipulations is greatly influenced by the *intraocular pressure*. Methods that are effective at a high pressure are not so when the pressure is low. This means that manipulations serving one and the same purpose must be performed differently before and after opening the globe.

When the intraocular pressure is *high*, the tissue in front of a cutting edge can be immobilized with a fixation instrument applied *anywhere* on the globe, for in this situation it will fixate the eye as a whole.

When the intraocular pressure is *low*, fixation is effective only when the tissue is grasped and immobilized *very close to the cutting edge* (Fig. 2.54c).

Intraocular pressure also affects the sharpness of cutting instruments. Blades that are sharp at high pressure can behave as blunt instruments when the pressure is low (see

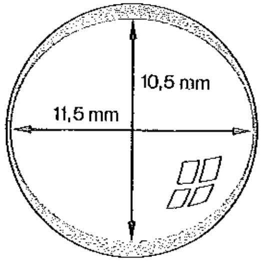

Fig. 5.1. **The corneoscleral boundary: zone of regular lamellar architecture and transition zone.** Externally, the vertical corneal diameter appears smaller than the horizontal, but internally the diameters are approximately equal in both directions. Thus, the transition zone at the limbus is wider superiorly and inferiorly than laterally and medially

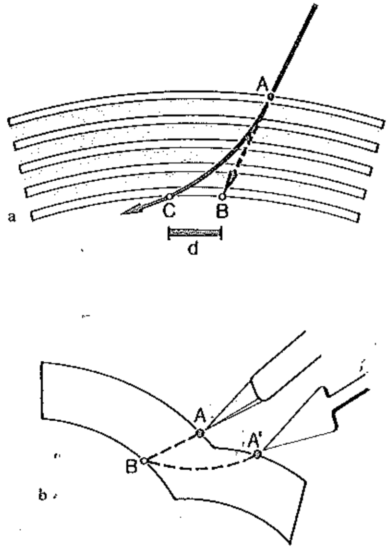

Fig. 5.2. **Effect of corneoscleral lamellar structure on cutting technique**

a Because the tissue has a lamellar structure, an incision started obliquely tends to stray onto the plane of the lamellae. Thus, a blade inserted at point *A* will not follow a straight path to point *B*, but will enter the anterior chamber at *C*. Allowance must be made for this, but the distance *d* of the lamellar deflection is difficult to estimate as it depends on the cutting ability of the blade and the sectility of the tissue.

b If the chamber is to be entered at a predetermined point *B*, a metal keratome (relatively blunt) needs to be inserted more peripherally (*A'*), while an ultra-sharp diamond blade can be inserted at *A* along a straight path aimed directly at *B*

Fig. 2.53). This must be considered when attempting to open the anterior chamber as well as in the dissection of lamellae. An incision made obliquely through the lamellae tends to stay on the original path when the intraocular pressure is high, but at low pressures it undergoes significant lamellar deflection and may even fail to reach the target (cf. Fig. 2.61). As it is difficult to assess the tendency toward lamellar deflection in a given situation, poor precision is always a risk when *oblique* incisions are used (Fig. 5.2). In work requiring high precision, then, these incisions should be avoided in favor of incisions made perpendicular or parallel to the lamellae. The *vertical incision* determines the precise depth of the cut, while *parallel dissection* determines the size of flaps.[1]

5.2 Dissection Technique

Reaching the Desired Depth. The depth of a vertical incision can be estimated from the *length of blade* immersed in the tissue (Fig. 5.3). In longer incisions it is easier to maintain a specified depth by fitting the blade with a *stop* (Fig. 5.4). However, this stop will function precisely only if the knife is held at a designated angle to the tissue surface (Fig. 5.4c). The preset depth can never be achieved along the entire cut, the difference depending on the shape of the blade and its guidance (Fig. 5.5).

Initiating the Lamellar Dissection. The major goal in the initial phase of a lamellar dissection is to create *sufficient space*, so that the blade can be rotated 90° for dissecting on the plane of the lamellae (Fig. 5.6).[2]

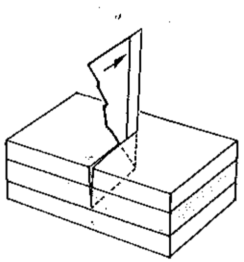

Fig. 5.3. Vertical incision. The depth of a vertical incision is estimated by the length of blade tip concealed by the tissue

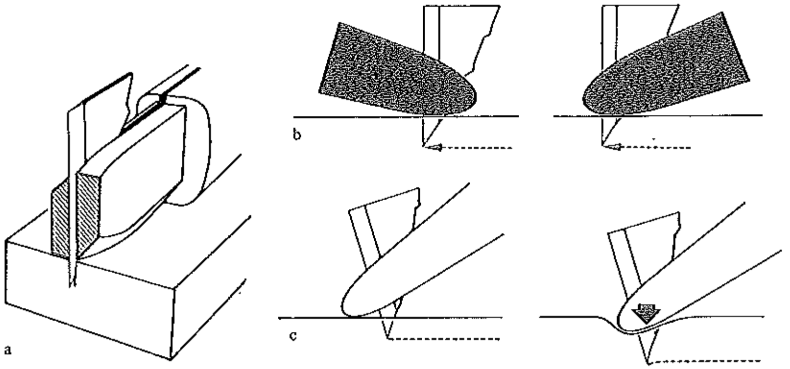

Fig. 5.4. Incision with a preset depth

a Example of a stop arrangement for a razor-blade holder. One jaw of the holder is square-edged and acts as a depth stop; the other jaw, which faces the surgeon, is beveled to facilitate visual control.

b The results are determined by the guidance direction of the cutting edge. They are not influenced by whether the blade is "pushed" or "pulled" through the tissue, although a forward incision (*right*) gives a better view of the tissue to be incised.

c The preset depth is reached only when the blade holder is held in a predetermined position. In other positions the entire preset blade length may not enter the tissue (*left*). If the holder is pushed down against compressible tissue (*right*), it may indent the surface and cut to a greater depth than the preset value

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[1] Examples: In the limbal transition zone: Narrow flaps for 3-step incisions, wider flaps for covering antiglaucomatous fistulae. In the cornea: Lamellar grafts. In the sclera: Pockets for intrascleral implants in buckling retinal detachment operations, lamellar sclerectomies for removal of uveal tumors.

[2] This step calls for high precision if the flap must have a uniform thickness to its outer edge, as in lamellar keratoplasty.

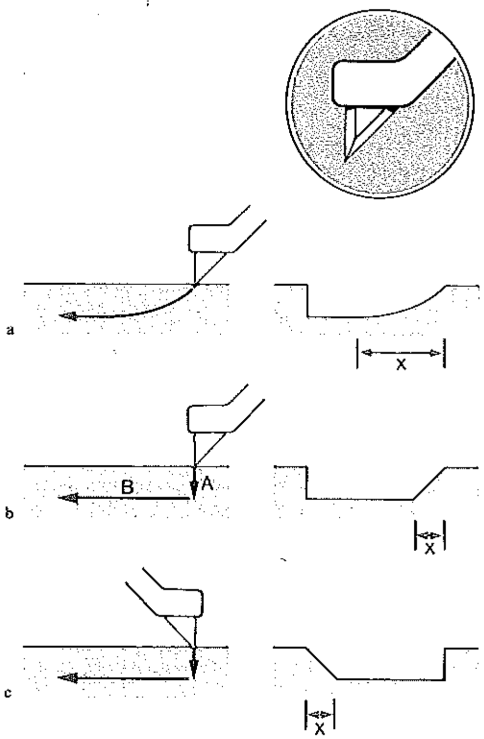

Fig. 5.5. Profiles of vertical cuts at preset depth. Shown here are cuts produced by a triangular diamond knife with front and rear cutting edges (inset).
Left: Paths traveled by the blade.
Right: Resulting cut profiles.
X: Portion of cut with insufficient depth.

a If the blade is gradually introduced into the tissue while moving forward (*left*), the initial part of the cut will be more superficial than planned (i.e., than preset with the stop).

b If the blade is thrust full depth into the tissue (*A*) *before* the horizontal motion (*B*) is begun, the cut will have the preset depth for almost its full length. Only the end profiles will vary depending on the shape of the blade. Here the blade is pushed, so the longitudinal cut profile is oblique at the beginning and vertical at the end.

c If the same blade is pulled, the cut profile is vertical at the beginning and oblique at the end

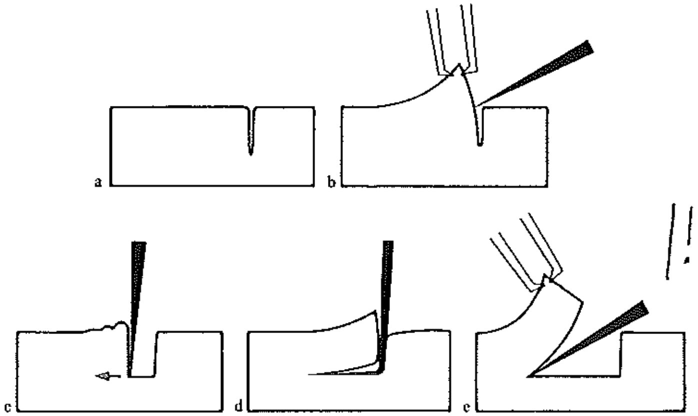

Fig. 5.6 Starting the lamellar dissection

a The tissue is incised to the predetermined depth as shown in Fig. 5.3 or 5.4.

b If the wound lip is picked up with a forceps to begin the lamellar dissection, the tissue becomes stretched, and it is difficult to assess accurately the depth of the incision. The blade has to be applied obliquely and may not reach the desired plane.

! **c** Precision is increased by passing the blade vertically to the base of the prepared groove and then pushing it laterally while keeping it in the upright position.

d Given the space limitations, a short angulated blade facilitates the initial undermining of the flap.

e As the undermined area offers sufficient space for maneuvering, the dissection may be continued with a blade inserted obliquely

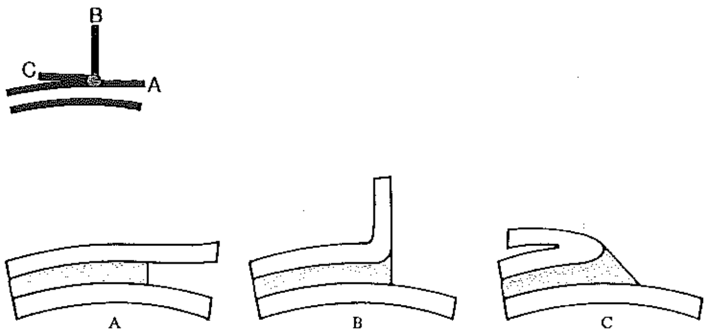

Fig. 5.7. **Dissection of lamellae.** The various techniques of lamellar dissection differ in how the mobilized flap is held while the interlamellar fibers are divided.
A: In situ flap
B: Elevated flap
C: Reflected flap
In *A* the fibers to be divided retain their anatomic position, but they are obscured by the overlying flap. *B* and *C* allow a direct view of the fibers but lead to the formation of a hinge fold, i.e., to tissue deformation with a change in tension

Continuing the Lamellar Dissection. When sufficient space has been created at the base of the cut for maneuvering the blade, various techniques are available for continuing the lamellar dissection. They differ with respect to visibility and tissue tension, and these are determined by the *angle* that is maintained *between the free margin of the flap and the plane of the dissection* (Fig. 5.7).

The dissection of an **in situ flap** (Fig. 5.8) is difficult to monitor visually and is suitable only in cases where the dissection can be performed *bluntly*.[3] The fibers to be divided are obscured by the overlying flap, and only the *position of the blade* can be evaluated. It is directly visible in the transparent cornea; in opaque tissue it can be checked indirectly by lifting the blade slightly to make a visible bulge in the tissue surface.[4]

Dissection with an *elevated* or *reflected flap* affords a clear view of the interlamellar fibers, so either technique is appropriate when *sharp* dissection is required. However, the elevating or reflecting maneuver deforms the tissue, and a hinge fold is produced which affects the position and tension of the fibers to be divided.

In the **elevated flap**, the interlamellar fibers at the ends of the hinge fold come under high tension, while the fibers at the center of the fold are lax (Fig. 5.9). This means that the cutting edge tends to encounter deeper fiber segments at the ends of the fold, and more superficial segments at the center. Another effect is that the sectility of the end fibers is increased, making those fibers easier to cut, and deviations of the dissection from the anatomical lamellar level are more likely to occur there than at the center. The fibers are less sectile centrally, where it is easier to maintain the plane of a given lamella.

The effects of the hinge fold can be reduced by *shortening its length*. This is achieved either by dividing the end fibers first and then gradually dissecting toward the center, or by subdividing a wide flap into narrower segments (see Fig. 1.54) if this is compatible with the operative goal.

In the **reflected flap** the tension of the interlamellar fibers does not stem directly from the forceps traction. Its distribution over the hinge depends far more on the *quantity* and *tension of the reflected tissue* (Fig. 5.10). Thus, a uniform tension can be maintained across the developing flap, regardless of the flap width, and this makes it easier to dissect a flap of even thickness. However, reflection of the flap bends the hinge, and the tissue offers resistance to this bending action. The degree of resistance for a given tissue and given intraocular pressure depends on the thickness of the reflected flap, so it can be decreased by reducing the flap thickness.[5]

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[3] This technique is most satisfactory for the blunt dissection of well laminated tissue, e.g., for lamellar keratoplasty in situations where healthy cornea is retained beneath the excised areas. The safety of the blunt dissection is enhanced by low sectility (low intraocular pressure).

[4] It is safe to perform the lifting movement separately from the cutting movement, i.e., to discontinue cutting while checking the blade position, and vice-versa.

[5] Where high precision is required, as in preparation of the bed for lamellar keratoplasty, it is best achieved by dissecting thin lamellae layer by layer.

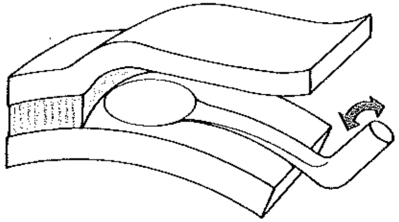

Fig. 5.8. **Lamellar dissection of an in situ flap.** Tissue deformation is slight and is minimal when the blade or its neck has the same curvature as the substrate (i.e., the ocular surface). The interlamellar fibers to be divided retain their natural position. Their tension depends on the thickness of the blade

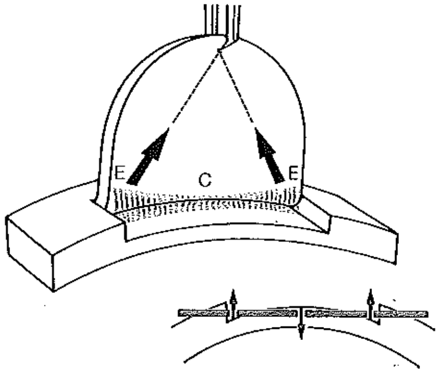

Fig. 5.9. **Hinge formation by an elevated flap.** Elevating the flap creates a hinge fold with characteristic effects: The lateral edges of the flap (*E*) are raised and the adherent fibers are made tense, while the center of the flap (*C*) is depressed and its fibers are lax. If division of the fibers is started at the edges, the hinge becomes shorter, and the central fibers gradually come under tension

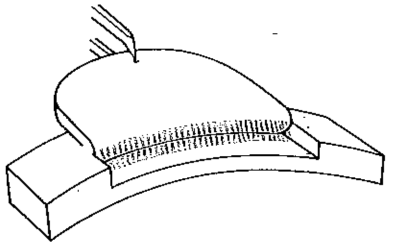

Fig. 5.10. **Hinge formation by a reflected flap.** When the flap is reflected as it is developed, the hinge tends to be curved; the tension of the interlamellar fibers depends on the flap thickness, and therefore the fibers can be made uniformly tense. Unequal tension develops only if there is substantial resistance to bending of the hinge axis

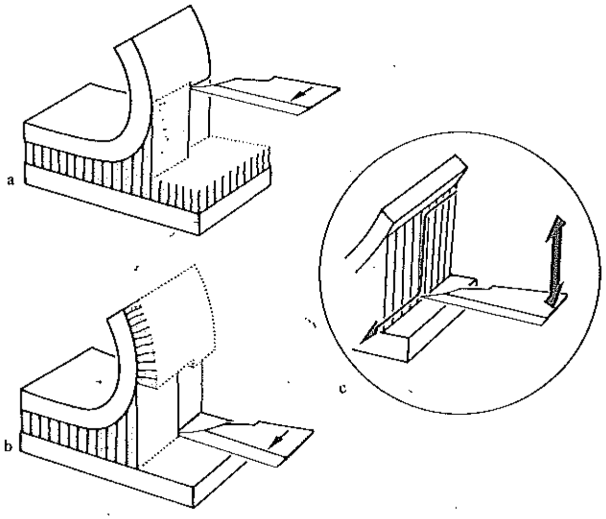

Fig. 5.11. **Development of an elevated flap.** The interlamellar fibers to be divided are perpendicular to the tissue surface, so a blade held perpendicular to the fibers is parallel to the lamellae themselves.

a Sectioning the fibers close to the flap yields a thin superficial lamella.

b Sectioning the fibers at their base yields a thicker flap.

c The plane of the dissection is adjusted by *vertical* movements of the blade

Since changing the position of the flap alters not only the tension on the interlamellar fibers but also their direction, the *direction of blade movements* must be changed accordingly. In the *elevated flap*, the fibers are pulled upward. Cutting the fibers at their upper end yields a thinner flap, while cutting at their lower end yields a thicker flap. Thus the flap thickness is changed by vertical movement of the blade (Fig. 5.11). In the *reflected flap*, the exposed fibers acquire a more horizontal orientation, so the flap thickness is changed by horizontal movements of the blade (Fig. 5.12).

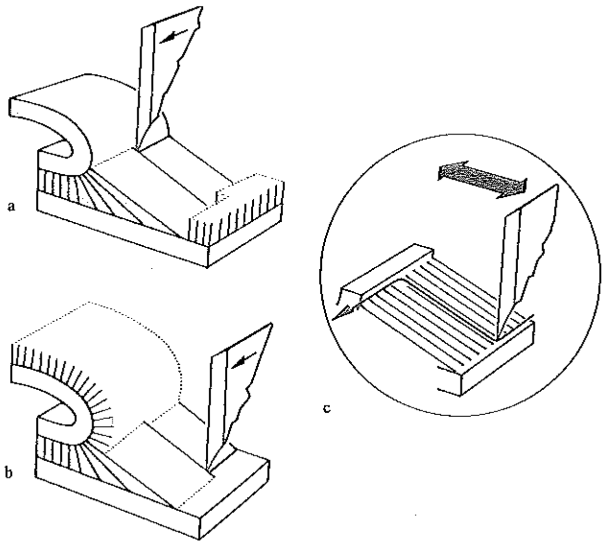

Fig. 5.12. **Development of a reflected flap.** The interlamellar fibers are oriented roughly parallel to the direction of the lamellae. The blade is held vertically.

a The superficial lamella is made thinner by dividing the fibers close to the fold.

b A thicker flap is obtained by sectioning the fibers near their base, or farther away from the fold.

c The plane of the dissection is adjusted by *horizontal* movements of the blade, i.e., by moving it closer to the fold or farther from it

5.3 Planning the Approach to the Eye Interior

Considerations in planning the approach for an intraocular procedure include not only the size of the incision but also its method of closure. The major concern is accessibility to the ocular interior, i.e., the *size of the useful access opening*. But equal attention must be given to planning the *wound closure*. Effective closure implies not only perfect geometric *apposition* of the wound margins but also a *watertight* wound that will maintain its integrity even under mechanical stress.

Both *anatomic* and *geometric* factors are relevant in these considerations.

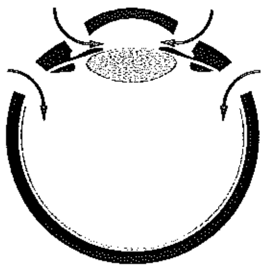

Fig. 5.13. **Approaches to the eye interior.** The *vitreous chamber* is reached with fewest complications through the pars plana. A more anterior approach is obstructed by the ciliary muscle and may provoke bleeding from the vessels of the ciliary processes. Approach behind the pars plana would perforate the retina. The *anterior chamber* is best approached from the limbal region so that any postoperative scars will not impair vision

5.3.1 Anatomic Factors in Opening the Globe

The *maximum possible length* of a useful access opening is limited by anatomic and topographic constraints. Anatomic factors also influence closure by determining the biologic healing potential of the wound (i.e., long-term closure).[6]

The best route of approach to the *vitreous chamber* is through the sclera over the pars plana of the ciliary body. The best approach to the *anterior chamber* is through the limbal region (Fig. 5.13).

In opening the **vitreous chamber**, the position of the pars plana can either be estimated from statistical data on the limbal distance or determined directly by diaphanoscopic transillumination (Fig. 5.14). Whether the incision is made radially or parallel to the limbus will depend on the relation of the proposed incision to the *course of the larger uveal vessels*. The exposed vessels themselves can be difficult to distinguish from surrounding pigmented tissue by visual inspection. They are identified either by diaphanoscopic transillumination or by diathermy, which produces appreciably less tissue shrinkage over the large vessels.[7]

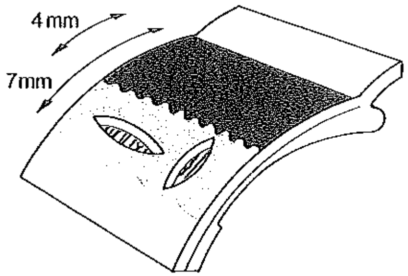

Fig. 5.14. **Approaches to the vitreous chamber.** The danger of hemorrhage on perforation of the vascularized uvea depends on the relation of the incision to the course of the vessels. Incisions that cross the vessels (*left*) expose multiple vascular branches, and a suitable access site can be found between them. Incisions parallel to the vessels (*right*) can be made longer without vascular injury but make it more difficult to locate an avascular interval. The *dark-shaded area* represents the ciliary zone that absorbs more light under diaphanoscopic illumination. *Note*: The limbal distance of the ora serrata is shorter nasally (6 mm) than temporally (7 mm)

There are various routes of approach to the **anterior chamber** from the limbal region, each offering advantages and disadvantages in terms of the surgical lesions inflicted on anatomic structures.

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[6] The healing potential of vascularized tissue (sclera, limbus) is greater than that of avascular tissue (cornea).

[7] Shrinkage is reduced over blood vessels because convective heat transfer is higher than in the neighboring avascular tissue (see Fig. 2.138).

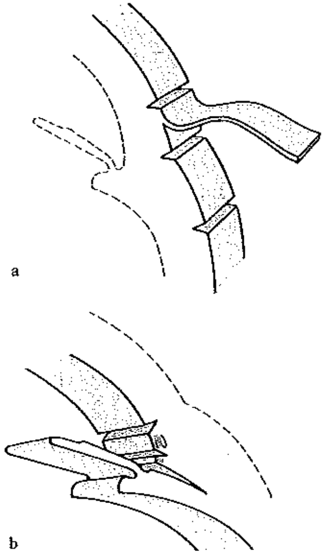


Fig. 5.15. **Approaches to the anterior chamber**

a *Outer surface*

Scleral incision:	Vascularized	Subconjunctival
Limbal incision:	Nearly avascular	
Corneal incision:	Avascular	

b *Inner surface*

Subciliary approach:	Implies cyclodialysis
Angular approach:	Traverses the structures of the chamber angle
Corneal approach:	Perforates Descemet's membrane and the endothelium

The routes of approach differ **externally** (Fig. 5.15a) in their *vascularity*, a major factor determining the quality and rate of wound healing and the potential for hemorrhage. They also differ in the opportunity for coverage with conjunctival flaps, which are useful for effecting rapid closure and wound repair but may obstruct the view of the operating field in the anterior chamber.

Internally (Fig. 5.15b) it is important to consider the relation of the incision to the structures of the chamber angle. A *corneal approach* enters the chamber at a distance from the iris root, facilitating the removal of synechiae and incarcerations and decreasing the likelihood of their formation in the postoperative period.

Entering *at the chamber angle* may damage the trabecular meshwork and the drainage channels. The peripheral location of the incision favors the development of synechiae.

A *subciliary approach* requires division of the ciliary attachment to the scleral spur and, unless permanent cyclodialysis is planned, is suitable only for narrow openings. It gives excellent access for the division of peripheral synechiae. It is also a good approach for injecting air or fluid to reform the anterior chamber against a high counterpressure, since the access opening is quickly tamponaded by the ciliary body when the cannula is withdrawn.

5.3.2 Geometric Factors in Opening the Globe

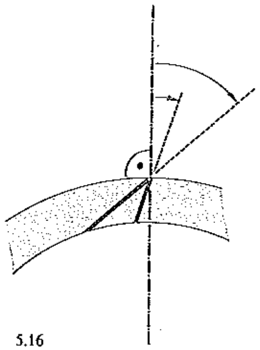
The geometry of the wound determines the *size of the useful access opening* in relation to the wound length that is visible externally. Geometric factors also determine the *quality of the wound closure* at the end of the operation (short-term closure).

Planning the Useful Opening

The *wound length* visible on the external surface of the eye gives no clue to the *useful opening* that is available to the operator. The lengths of the external and internal openings may differ greatly owing to the thickness of the ocular wall.

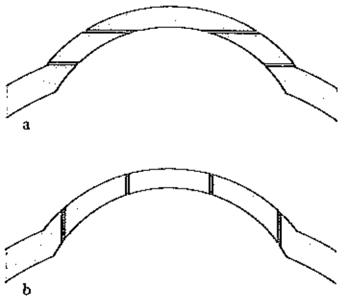
The ratio of the internal and external openings for a given incision technique is influenced by the **width of the wound surfaces**. As the wound surface becomes wider, it is more likely that a large discrepancy will exist between the external and internal openings. The width of the wound surface in turn depends on the *angle between the wound surface and the ocular surface* (Fig. 5.16) and on the level at which the *incision* is made (Fig. 5.17). The ratio of the inner and outer wound length is further influenced by the shape of the cutting instruments (Fig. 5.18).

Access through a **minimal opening** greatly limits the mobility of an inserted instrument (Fig. 5.19); but *several* such openings spaced widely apart can allow virtually the same free mobility as a single large opening while avoiding the closure problems that may be associated with a large incision. Thus, the necessary size of the access opening is determined less by the need to insert instruments than by the *size of the tissue parts* that must be removed from the eye.



5.16

Fig. 5.16. **Width of the cut surface.** The width of the cut surface depends on the angle of the incision relative to the perpendicular on the globe surface

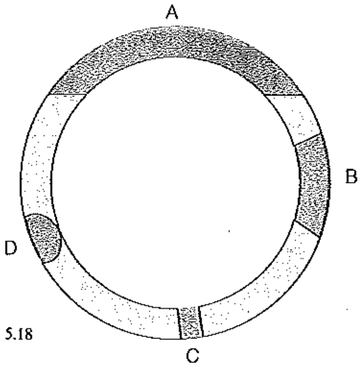


5.17

Fig. 5.17. **Change in the cut surface on parallel shift of the incision.** Parallel incisions in a thick-walled dome (such as the cornea) have surfaces of varying size.

a In incisions parallel to the iris, the area of the cut surface (*red*) increases toward the apex.

b In incisions perpendicular to the iris plane, the cut surfaces become smaller toward the apex



5.18

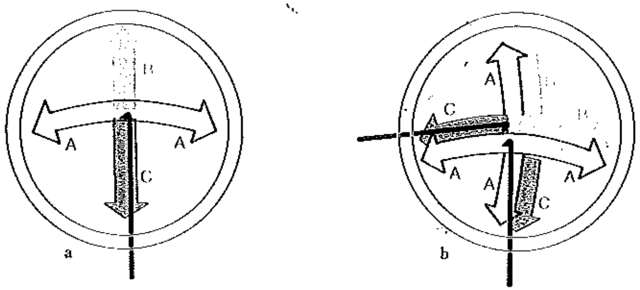
Fig. 5.18. **Internal and external wound lengths for various types of incision**

A Cataract knife incision: The discrepancy between the internal opening and external wound length is substantial.

B Keratome incision: The discrepancy is smaller.

C Stab incision with a stab knife: Both wound lengths are equal.

D Incision with a pointed knife: The internal and external openings do not depend on instrument shape and can be fashioned as desired. Here the internal opening was made very small to assist closure, and the external opening was made large for better instrument maneuverability



5.19

Fig. 5.19. **Limitation of the mobility of instruments introduced through small openings**

a Assuming that a given instrument has only one working characteristic in each direction of motion, i.e., swiveling (*A*), advance (*B*), and withdrawal (*C*),[8] it is clear that only one type of action can be performed in the anterior chamber in each direction.

b If an additional small opening is placed 90° from the first, different types of action can be performed using the same instrument

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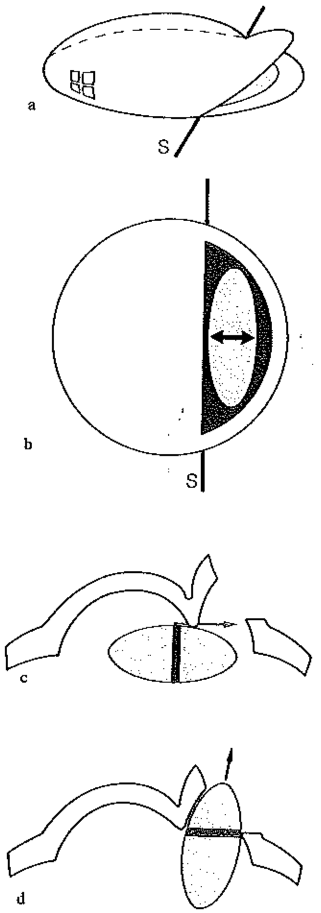
[8] For example, cystitomes are blunt in A, somewhat less blunt in B, and sharp in C (see Fig. 8.33); angled injection needles are sharp in A and blunt in B and C (see Fig. 8.34); phacoemulsifying probes are sharp in A and blunt in all other directions.



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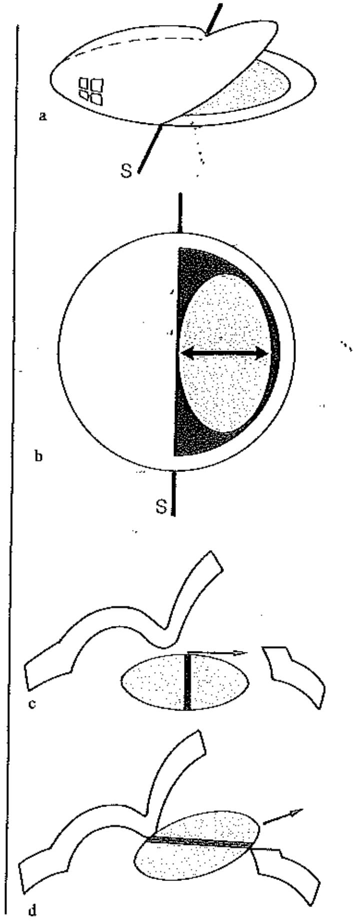

5.21

Fig. 5.20. Effect of hinge formation on the useful opening for lens delivery. Position of the hinge fold in a 120° section

a Perspective view of the hinge fold. *S*: Hinge axis.

b Overhead view: The fold constricts the opening for lens delivery. *Red:* Transverse lens diameter that must negotiate the opening on the plane of the hinge axis.

c Side view: The fold in the 120° section may form *in front of* the largest transverse lens diameter. That part of the lens is driven *against* the fold at the start of the expulsion maneuver, with a danger of endothelial damage.

d Reorientation of the lens during delivery: To negotiate the constricted opening, the lens must rotate into an upright orientation causing a corresponding volume shift in the vitreous chamber

Fig. 5.21. Effect of hinge formation on the useful opening. Position of the hinge fold in a 180° section

a In this section the hinge fold is farther back from the exit.

b This results in considerable gain of space, and the opening can accommodate a large lens diameter.

c The hinge fold is positioned *over* the greatest lens diameter, and the lens moves *away from the fold* on delivery. Thus, only smaller portions of the lens pass beneath the fold, and there is less risk of endothelial touch than in Fig. 5.20c.

d Emergence of the lens through the opening: The larger opening necessitates little lens reorientation during delivery, and the effects on the vitreous chamber are milder

The useful opening in **large incisions** is determined not only by the geometry of the incision in the ocular wall but also by the *position of the hinge axis.* The fold may constrict the useful opening and render it too small for the delivery of tissue parts that it could otherwise accommodate. Because of the hinge phenomenon, procedures in which the ocular incision is to be opened by raising a flap will require an incision of greater length than in other procedures (Figs. 5.20 and 5.21).

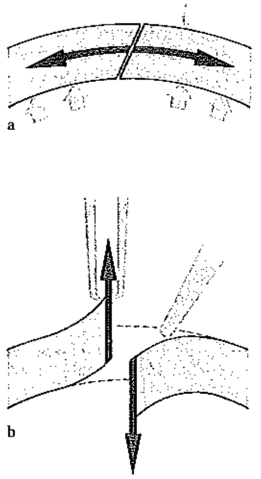

Fig. 5.22. Mechanisms of wound opening

a Gaping: A wound gapes when its surfaces are pushed or pulled apart by forces applied *tangentially.*

b Flap mechanism: A wound can be opened in a *perpendicular* direction by elevation or depression of the wound margin (e.g., with a fixation forceps or spatula)

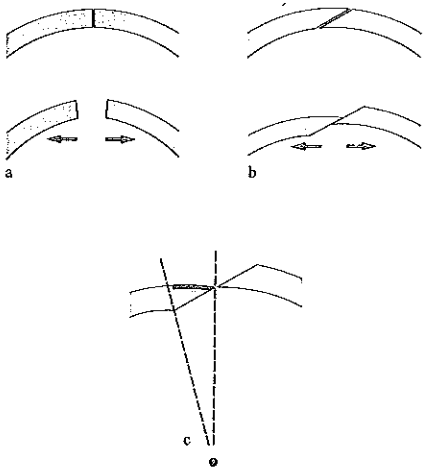

Fig. 5.23. Gaping of wounds

a In a perpendicular incision, the slightest dehiscence is sufficient to cause gaping.

b Oblique incisions form "valvular" openings that can remain watertight even when their edges are shifted.

c When the distance of the shift equals the projection of the wound surface onto the ocular surface (*red*), the incision begins to gape

Planning the Closure

In planning the wound closure, it is important to analyze the behavior of the incision in response to tangential and perpendicular forces (Fig. 5.22). *Tangential forces* are produced by an increase in wall tension (e.g., a rise of intraocular pressure), and they cause the edges of the incision to separate laterally ("wound gape"). *Perpendicular forces* are exerted locally (by instruments or by ocular structures themselves), and they either elevate or depress the wound margin.

Gaping occurs if the internal wound margin on one side can no longer meet the external margin on the other side, so that a communication is formed between the interior of the eye and the outside air. In a *perpendicular incision,* even the slightest shifting of its margins will

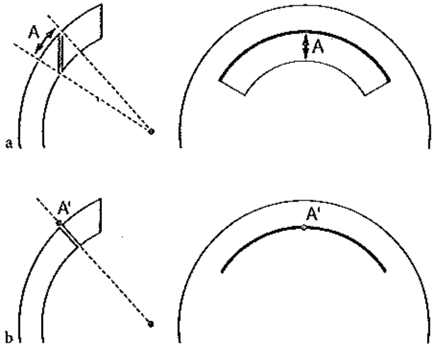

Fig. 5.24. Margin of watertightness

a The larger the projected area of wound surface onto the ocular surface (*A*), the more competent the valve.

b In perpendicular incisions the deep and superficial wound edges (as projected onto the surface) coincide, so the projection of the wound surface is a line. The margin of watertightness in a perpendicular incision is zero cause gaping (Fig. 5.23a). Any incision that is not perpendicular produces a *valvular opening* that will remain closed when its edges shift relative to each other (Fig. 5.23b). The permissible extent of this shift, called the *margin of watertightness*, is expressed by the **valve rule**: *Incisions through the ocular wall produce valves whose margin of watertightness equals the projection of the surface of the incision onto the ocular surface* (Fig. 5.24).[9]

When the intraocular pressure rises, then, a perpendicular (= nonvalvular) incision will always gape[10] while an oblique (= valvular) incision will close even more tightly.[11] Thus, a valvular incision is not opened by a general rise of intraocular pressure, and it can be opened only by the action of local perpendicular forces which raise or lower the wound margin (see Fig. 5.22b).

This perpendicular mechanism of wound opening is applicable to all incisions that do not follow the path of a great circle on the globe (Fig. 5.25). The movable portion of the ocular wall, called the flap, is rotated about the imaginary "hinge" that connects the ends of the incision.[12]

Whether the flap can rotate outward or inward (i.e., can be raised or depressed) depends on whether the outer or inner wound margin is overriding. Rotating the flap may or may not open the wound. This depends on the location of the hinge axis and is defined in the "**hinge rule**": *A wound acted on by a perpendicular force will remain watertight if its hinge axis lies entirely within the wound surface.*

For **flaps that rotate outward**, the hinge rule states that the wound will remain watertight if the imaginary hinge axis does not intersect the internal wound margin when both are projected onto the ocular surface (Fig. 5.26). Thus, we can draw a distinction between wounds which are watertight by virtue of their geometry, and those which are not. The decisive factor is the length-to-width ratio of the wound surface: Long incisions made at a steep angle are easily opened, whereas short incisions made at a shallow angle tend to remain watertight (Fig. 5.27). Valvular incisions that follow a great circle path on the eye (Fig. 5.25a) are watertight by the hinge rule, regardless of their length.[13]

The distinction between watertight and non-watertight wounds is important from the standpoint of operative tactics. Watertight wounds will remain effectively closed of their own accord.[14] Nonwatertight wounds, on the other hand, require suturing for secure closure. The purpose of the sutures is to subdivide the wound into segments which individually are watertight by the hinge rule. The sutures (or more precisely, the points where the stitches cross the external wound margin) function as the artificial vertices of new hinge axes (Fig. 5.28). As the hinge rule implies, the sutures should be spaced so that the new hinge axes do not intersect the internal wound margin[15] (Figs. 5.29, 5.30).

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[9] The valve rule applies only if the wound is able to form a functional valve. Incongruent wound surfaces (incongruent grafts, trauma) and incarcerated foreign matter (tissue fragments, foreign bodies, viscous substances) make the wound incompetent as a valve.

[10] This tendency makes the perpendicular incision excellent for antiglaucomatous fistulas. The difficulty is to keep the blade on a perpendicular path through multiple tissue layers.

[11] Owing to their valvular properties, keratome and cataract knife incisions could be left unsutured in earlier times when suitable threads and needles were unavailable.

[12] Rotating a flap creates a fold only if the tissue has a "hinge fold capability," i.e., if the forces applied to the flap are transmitted to the ends of the incision. The necessary rigidity either is inherent in the tissue or is produced secondarily by the application of tension (with forceps or by repressurization of the globe).

[13] Such wounds are apt to *gape*, however, if the incision is perpendicular (i.e. nonvalvular).

[14] Provided there is no obstacle between the wound surfaces. Tissue incarceration may be the surgical goal (iridencleisis) or may occur as an undesired complication (iris prolapse, vitreous prolapse).

[15] As projected onto the ocular surface.

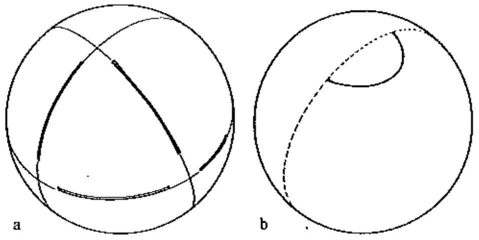


Fig. 5.25. **Incisions with and without flaps**

a Incisions that follow a great circle path on the eye cannot form flaps.

b Flaps are formed by incisions that do not lie on a great circle

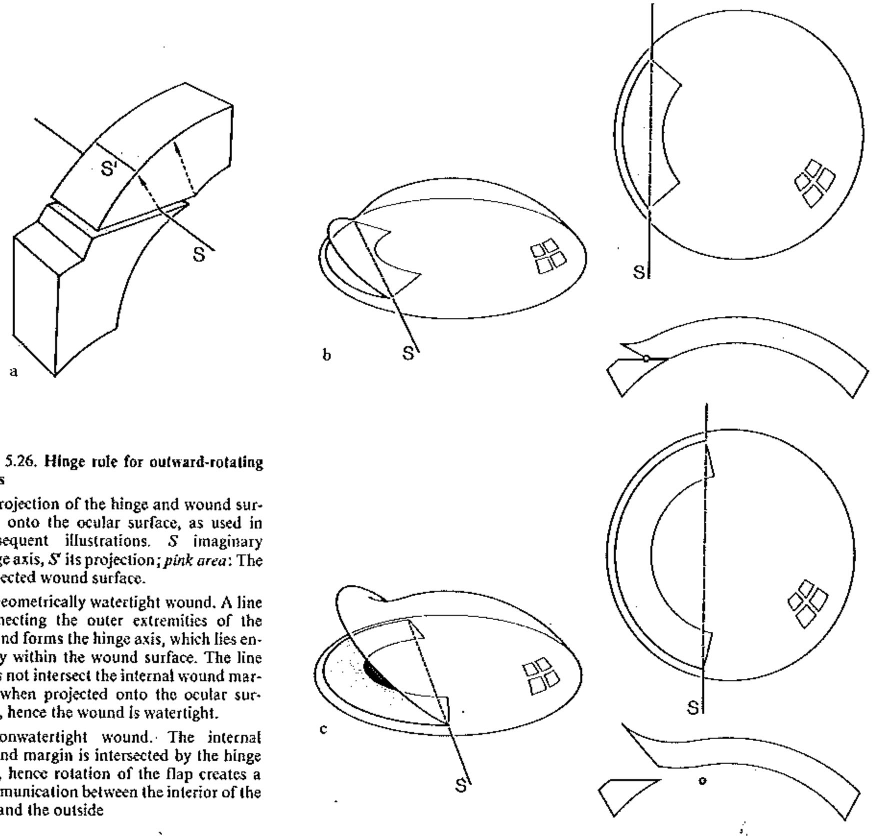


Fig. 5.26. **Hinge rule for outward-rotating flaps**

a Projection of the hinge and wound surface onto the ocular surface, as used in subsequent illustrations. *S* imaginary hinge axis, *S'* its projection; *pink area*: The projected wound surface.

b Geometrically watertight wound. A line connecting the outer extremities of the wound forms the hinge axis, which lies entirely within the wound surface. The line does not intersect the internal wound margin when projected onto the ocular surface, hence the wound is watertight.

c Nonwatertight wound. The internal wound margin is intersected by the hinge axis, hence rotation of the flap creates a communication between the interior of the eye and the outside

Fig. 5.27. **Sample applications of the hinge rule.** *Left*: In wounds of equal length, the width of the projected wound surface determines whether or not the wound is geometrically watertight. *Right*: In wounds with (projected) surfaces of equal width, the wound length determines watertightness.

The incisions in the *top* row are geometrically watertight; those in the *bottom* row are not watertight and require sutures for closure

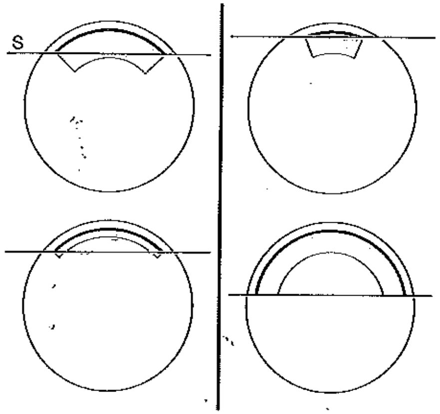
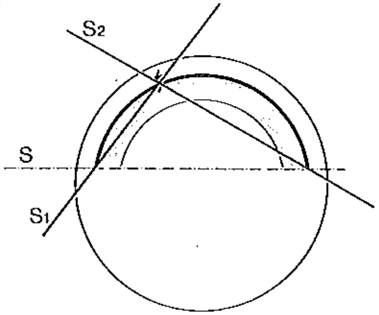


Fig. 5.28. **Use of sutures to establish watertightness.** The suture divides the wound into segments whose watertightness is determined by the new hinge axes (S_1 and S_2). The segment on S_1 is watertight, while that on S_2 must be subdivided further



Incisions with narrow surfaces require more sutures to effect closure than incisions with wide surfaces (Fig. 5.31). Closure is more difficult in *perpendicular* incisions, because it is impossible to create a new hinge axis that does not intersect the internal wound margin.[16] In theory an infinite number of sutures would be required, but in practice the problem is solved by the use of compression sutures.[17] Conversely, the closure of *valvular* incisions is satisfactorily accomplished with simple apposition sutures.

Inward-rotating flaps act as a valve against forces that press the flap outward. Consequently the wound remains watertight when the intraocular pressure rises, but it may be opened by a force that presses the flap inward. Again, the *hinge rule* determines whether the wound will remain watertight when the flap is turned. But in contrast to outward-rotating flaps, an inward-rotating flap remains closed as long as the hinge axis does not intersect the *external* wound margin. In the sutured wound, moreover, the points of *intramural* (deep)

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[16] As projected onto the ocular surface.

[17] The placement of these sutures is then determined by the size of the compression zones (see Fig. 2.109). Compression sutures always distort the tissue, as discussed in Chap. 2.1.4.

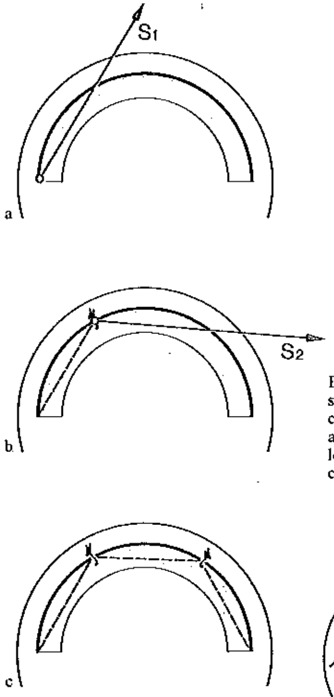

Fig. 5.29. **Determining the minimum number of sutures required for watertight closure of a wound**

a The location of the first suture is found by drawing a line (S_1) from the outer end of the incision that just bypasses the interior wound margin. The suture is placed at the point where that line crosses the external margin of the incision.

b Another line (S_2) is drawn in the same way from the first suture, and the second suture is placed at its intersection with the external wound margin.

c A line from the second suture reaches the opposite end of the incision without crossing the internal margin. Therefore no further sutures are necessary to effect a watertight closure in this example

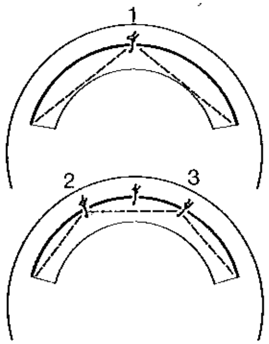

Fig. 5.30. **Increasing the safety margin in suturing.** "Safety sutures" can maintain closure in the event that a suture placed as described in Fig. 5.29 breaks or comes loose. In the drawing above, suture *1* is capable of dividing the wound into watertight segments. Sutures *2* and *3* are safety sutures placed so that their hinge axes do not intersect the interior wound margin. Note that the sutures are not spaced evenly along the wound line, but 2 and 3 lie closer to suture *1*

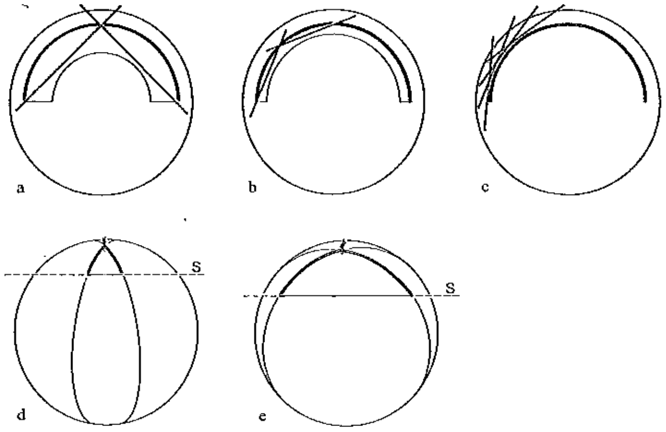

Fig. 5.31. **Minimum number of sutures needed for outward-rotating flaps**

a If the wound surface is broad enough, a single suture may be sufficient.

b Narrower wound surfaces require more sutures.

c In a perpendicular wound each hinge axis forms a chord that intersects the (projected) wound margin. In theory, an infinite number of sutures would be required.

d and **e** *Suturation of "gothic arch" incisions.* Flap wounds made by two incisions which follow a great circle path are divided into two watertight segments by a single suture placed at the apex of the arch, regardless of the size of the flap. Only the outer wound edges are shown in the drawings; the projection of the wound surface is omitted (for a practical example of the gothic arch incision, see Fig. 5.63)

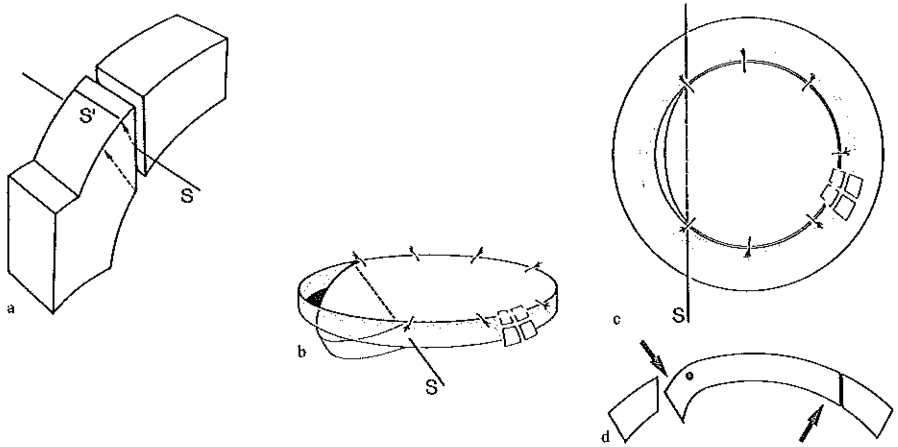

Fig. 5.32. Hinge rule for inward-rotating flaps (illustrated for the suturing of a trephine disk)

a Projection onto the ocular surface. *S* hinge axis; *S'* projected hinge axis; *pink area*: Projected wound surface.

b, c If the projection of the imaginary hinge axis intersects the external wound margin, the wound will open when the flap is rotated inward.

d Outward pressure cannot open the flap (*right arrow*). Inward pressure will open the wound if the hinge axis lies outside the projected wound surface (*left arrow*)

suture passage form the vertices of the new hinge axes (Fig. 5.32).

The key factor in determining the correct spacing of the sutures, thus, is the distance of the point of deep suture passage from the external wound line (Fig. 5.33). The wider the wound surface and the deeper the suture, the fewer sutures are needed to effect satisfactory closure[18] (Fig. 5.34).

Incisions whose external wound line follow the path of a **great circle** represent a special case. Incisions of this type cannot be opened by rotation about an axis (see Fig. 5.25a).

As a result, flaps that are formed by two such segments ("gothic arch" flaps) have interesting properties (Figs. 5.31d and e): They can be effectively closed by a single suture placed at the apex of the flap, because the suture divides the wound into two watertight segments, regardless of the length of the incisions or the apex angle of the arch.

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[18] Note the difference between the suturing of outward and inward rotating flaps: In the outward rotating flap, the *bridging* parts of the suture loops form the ends of the hinge axis, so the depth of the suture is irrelevant for closure (it is relevant only for a secure grip of the loops in the tissue). Conversely, in the inward rotating flap, the *intramural* passages of the thread form the end of the hinge axis, and so the depth of the suture is critical (compare with Fig. 5.26).

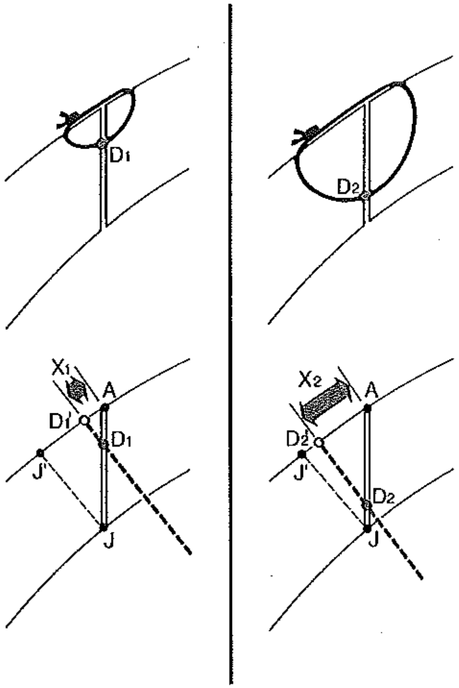

Fig. 5.33. Location of hinge axis for inward-rotating flaps. The points of deep suture passage *D* form the new vertices of the hinge axis. The deeper the suture, the greater the projected distance *X* from the external wound margin *A*.
D' Projection of suture passage onto the ocular surface.
J Interior wound margin; *J'* its projection onto the ocular surface.
Left: Superficial suture
Right: Deep suture

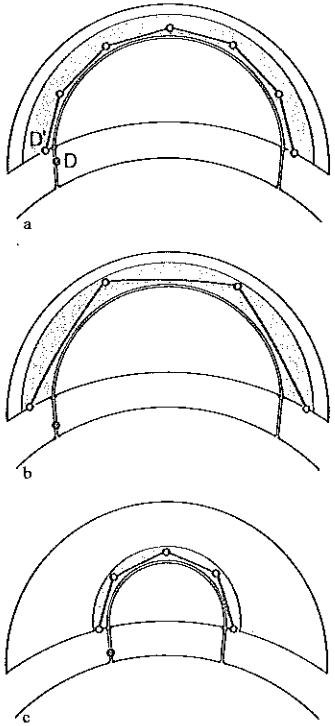

Fig. 5.34. Minimum number of sutures needed to divide an inward-rotating flap into watertight segments (illustrated for a trephine disk). Effect of suture depth (*D*) and width of wound surface. *Pink*: Projection of the wound surface onto the ocular surface.

a With superficial sutures the vertices of the hinge axes project close to the external wound margin. The number of sutures is correspondingly large.

b With deep sutures the vertices are more distant from the external wound margin, and fewer sutures are needed.

c If the trephine disk is small, the projected wound surface is narrowed, and the projected vertices are less distant from the external wound margin (despite the same suture depth as in **b**). Despite the shorter wound length, more sutures are required than in **b**

5.3.3 Comparison of Different Incision Profiles

Several criteria should be considered when selecting the profile of an incision:

Freedom of choice of anatomic reference points (Fig. 5.35). When the incision is made on a single plane, the positions of the external and internal wound margins correlate with the inclination of the cut surface. In multiple-plane incisions they are mutually independent, and they can be varied as needed while the incision is performed.

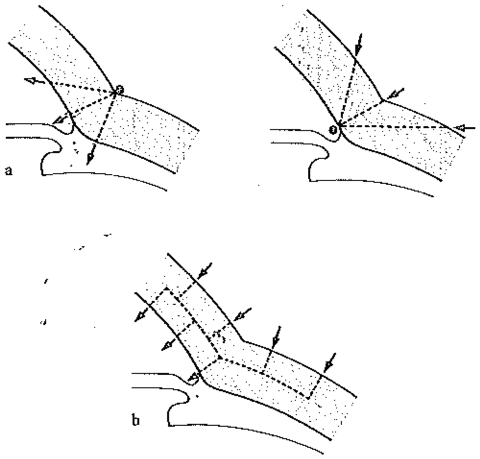

Fig. 5.35. Anatomic factors in selecting the incision profile

a Single-plane incisions: Once the position of the external (*left*) or internal (*right*) wound margin has been established, the location of the remaining wound margin (i.e., the width of the wound surface) depends on the angle at which the incision is made (*arrows*).

b Multiplane incisions: The positions of the external and internal wound margins are mutually independent and can be varied during the course of the incision according to requirements of specific situations (see Fig. 5.63)

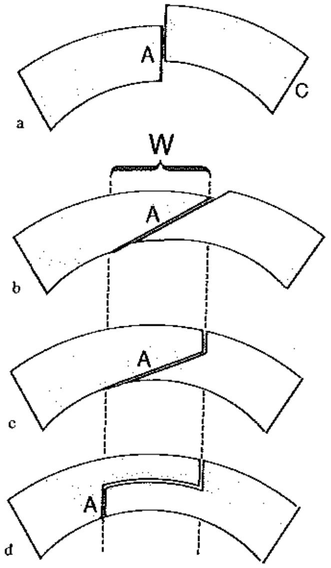

Fig. 5.36. The properties of various incisions

	Margin of water-tightness	Precise apposition	Lamellar deflection	Tissue thickness on opening of chamber	Technical complexity of incision
a) Perpendicular incision	0	easy	none	A = C	+
b) Single-plane oblique incision	W	difficult	high	A ⩾ C	+
c) 2-plane step incision	W	easy	low	A > = < C depending on W	+ +
d) 3-plane step incision	W	easy	none	A < C	+ + +

A = thickness of tissue layer that must be sectioned as a last step prior to entering the chamber.
C = corneal thickness.
W = projection of wound surface onto ocular surface

Margin of watertightness (Fig. 5.36). Both the *valve rule* and *hinge rule* state that the tendency of a wound to remain watertight when acted on by a tangential or perpendicular force depends on the width of the wound surface as projected onto the ocular surface. This dimension generally serves to characterize the stress resistance of a wound.[19]

Apposability. *Perpendicular* wound surfaces facilitate accurate approximation of the wound margins. The vectors created during suturing cannot cause tangential shifting of the wound margins. Only perpendicular shifts are possible, but these are easily recognized because they create a steplike incongruity which, even if slight, is plainly visible by the interruption of the surface reflex. *Oblique* wound surfaces are more difficult to approximate precisely because the edges can easily shift relative to each other (Fig. 5.36b). Also, it is more difficult to detect faulty apposition due to the angulation of the wound edges.

Lamellar deflection. Incisions made at an angle to the plane of the lamellae tend to undergo deflection, with a corresponding loss of precision.

Tissue resistance upon entering the globe. The lower the tissue resistance in the critical phase of the incision (last step before entry into the eye), the less force is required, and the less the danger of inadvertent damage to intraocular structures. This resistance depends on the thickness of the tissue layer that must be divided in the last phase of the incision.

Technical complexity. The technical complexity of the incision, and thus the time required to complete the incision, increase with the number of direction changes involved in making the incision.

5.4 Methods of Opening the Anterior Chamber

The critical moment at which the blade reaches the anterior chamber is easily recognized: A polished surface that appears mat while still in the corneal stroma becomes bright again on entering the anterior chamber. Once inside the chamber, instruments appear displaced from their true position because of the higher refractive index of the cornea and aqueous fluid (Fig. 5.37). This is not a problem as long as the instruments are used entirely within the chamber, since all objects are viewed under the same optical conditions. But if it is necessary to make a counterincision from inside the chamber, allowance must be made for the apparent upward deflection by aiming the point of the blade higher than the planned site of emergence on the outer corneal surface.

If aqueous escapes when the anterior chamber is entered, this will affect not only spatial tactics but also tissue tactics due to the consequent fall of intraocular pressure and loss of tissue tension. Initially sharp *blades* will suddenly behave as if dull, and *fixation instruments* that initially fixed the entire globe will exert only a local action and deform the tissue. The effects on the conduct of the section are so profound that it is useful to distinguish between methods whose success depends on *avoiding aqueous loss* and methods in which *aqueous loss is acceptable* and due allowance is made for the fall of intraocular pressure.

Fig. 5.37. Visual control in the anterior chamber. The surface of polished instruments appears mat when between the corneal wound surfaces but becomes bright on entering the aqueous humor. Instruments in the anterior chamber appear to be bent upward, the degree of this effect varying with the viewing angle.[20] In reality the tip is lower in the chamber than it appears when viewed from the outside. If the tip is to emerge at the limbus, for example, the surgeon should aim for a point about 1 mm higher on the outer corneal surface (*red*). If he aims directly for the limbus, the counterpuncture will be too low

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[19] The margin of watertightness determines closure not just at the end of surgery but also in the postoperative period during cicatrization. Therefore, the risks of early suture removal decrease when wounds have a large margin of watertightness.

Example: When correction of astigmatism by early suture removal is planned, incisions with a large margin of watertightness are preferred.

[20] Distortion is minimal from an overhead perspective (e.g. a coaxial microscope) and more pronounced with an oblique view.

5.4.1 Keratome Section

Keratomes have a wedge-shaped blade whose preferential path lies on one plane.[21] The shape of the cutting edge determines the vector components created when the blade is advanced (Figs. 5.38, 5.39).

Owing to the wedge shape of the keratome blade, the incision remains *watertight* as long as the blade is advanced. The intraocular pressure does not fall, the tissue remains sectile, and the diaphragm remains stationary until the point of the blade reaches the opposite chamber angle. The *length of the incision* that can be made under these optimal conditions is determined by the width of the keratome blade (Fig. 5.40). However, the geometry of the blade will cause the wound to open if the slightest error is made, i.e., if the blade is raised, lowered, or tilted to any degree. This excludes any possibility of corrections during the keratome incision (Fig. 5.42), for the diaphragm will bulge forward as soon as aqueous escapes. The section must be completed without delay, therefore.

When the keratome is *withdrawn*, the point is first removed from the pupil region to avoid injury to the lens, which now moves forward to a more anterior position. This is done by raising the point of the keratome while simultaneously moving it toward the side (Fig. 5.41c). The section can still be extended at this time. If this is done in a smooth *rotary motion*, aqueous loss can be prevented and tissue sectility preserved (Fig. 5.41b). But if the keratome is moved *laterally* as it is withdrawn, aqueous will escape. Although this makes the tissue more difficult to cut, the section can proceed by utilizing the pull-through vector component of the cutting edge (Fig. 5.41a).

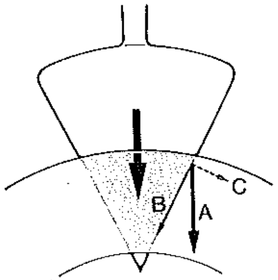


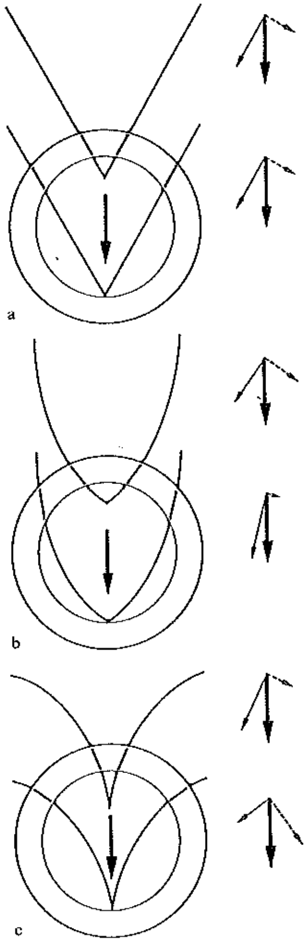
Fig. 5.38. Force vectors of a keratome. Advancing the keratome (*A*) creates a thrust component (*C*) that enlarges the incision and also a pull-through component (*B*) that improves the cutting efficiency of the blade

Fig. 5.39. Cutting properties of various keratomes ►

a In keratomes with straight cutting edges, the relation between the thrust and pull-through vectors remains fairly constant throughout the incision. However the length of the tissue segment to be divided increases and, with it, the resistance.

b In keratomes with convex cutting edges, the pull-through vector predominates so that the cutting ability of the blade steadily increases.

c In keratomes with concave edges, the thrust vector predominates so that cutting ability decreases as the incision proceeds. The resulting incision differs from that in **b** by the position of the hinge axis; in **b** it facilitates closure, whereas here it facilitates opening



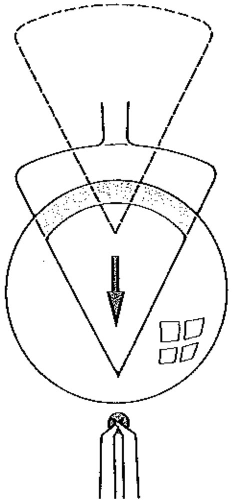


Fig. 5.40. Advancing the keratome. The tip is directed toward the fixation forceps (see also Fig. 3.19)

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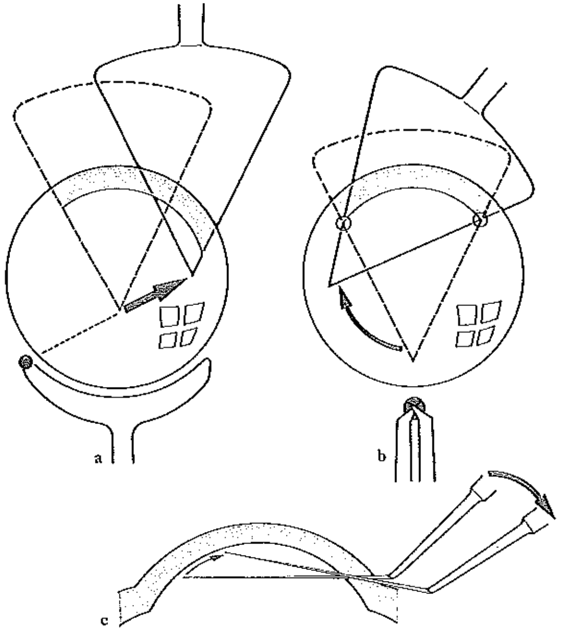
[21] If the two cutting edges are asymmetrically ground so that their preferential paths are on different planes, the incision will deviate as shown in Fig. 5.42. So the blade, especially if large, must be ground with extreme precision as to symmetry.



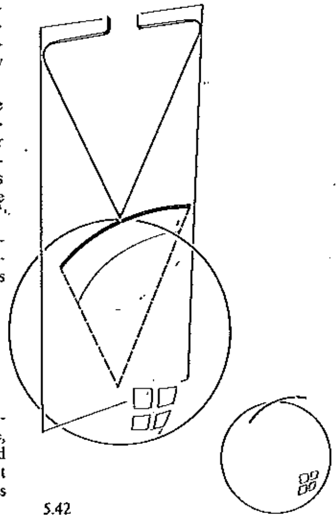
5.41

Fig. 5.41. Withdrawing the keratome

a Lateral blade movement to enlarge the incision: On withdrawal the keratome tip is moved laterally to remove it from the pupil region. The section can be simultaneously extended by adding a pull-through motion of the blade. A broad fixation forceps aids the lateral motion by offering resistance to lateral vectors.

b Rotation of the keratome to extend the section: The ends of the incision (*red circles*) can be sealed during this maneuver by keeping the cutting edges in firm contact with them. A small fixation forceps aids compensatory counterrotation of the globe.

c To avoid injury to the bulging diaphragm when the anterior chamber empties, the keratome tip is raised (handle is lowered) during withdrawal



5.42

Fig. 5.42. If the guidance path of the keratome is not parallel to the limbal plane, the incision may transgress the limbus and enter the sclera. Any attempt to correct the position of the blade will allow loss of aqueous

5.4.2 Cataract Knife Section

Cataract knives have a narrow, pointed blade that is used first to *puncture* the chamber and then to *section* it from within (Fig. 5.43). The various types of cataract knife differ chiefly in the shape of the point, which determines whether the blade will deviate from the guidance direction when advanced through tissue (Fig. 5.44).

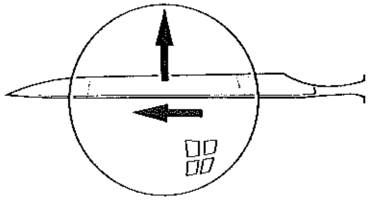


Fig. 5.43. Force vectors in the cataract knife section. The vector for making the puncture and counterpuncture and that for performing the section are separate from each other and are mutually perpendicular

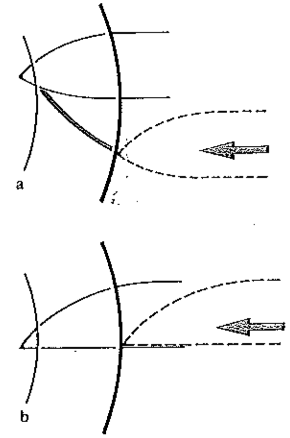
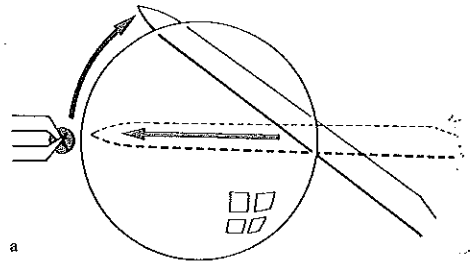


Fig. 5.44. Cutting properties of the cataract knife tip

a Knives with a curved back deviate in the direction of the cutting edge when thrust straight into the tissue.

b Knives with a straight back do not deviate from the guidance direction



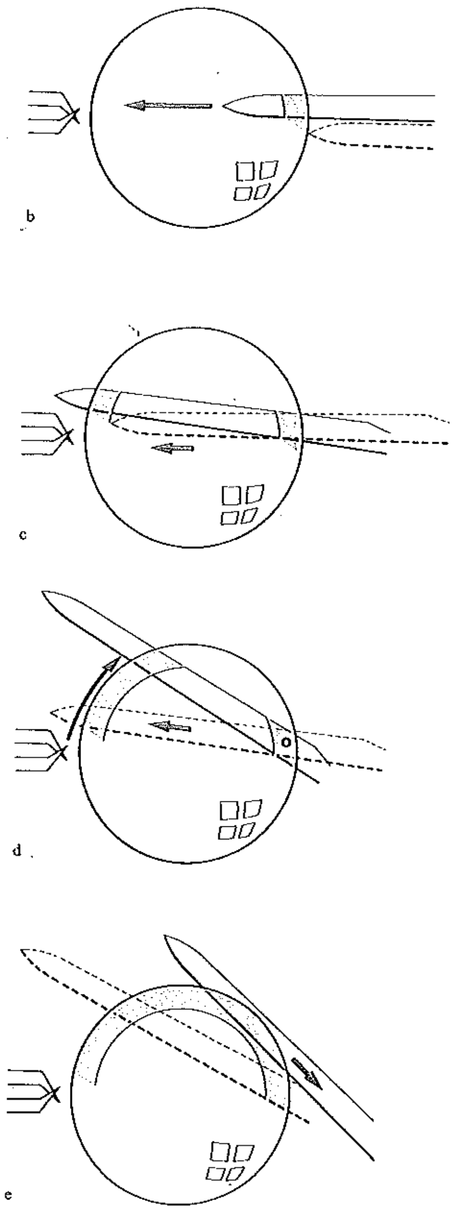


Fig. 5.45. Cataract knife section with lateral fixation (favoring the puncturing maneuver)

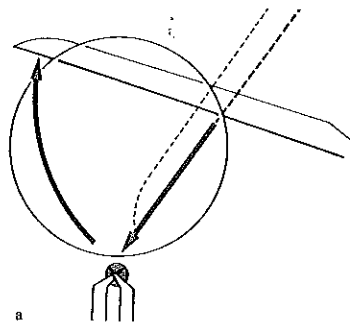
a Principle: The vectors of the puncturing and sectioning motions are directed through the application site of the forceps.

b The tip is directed toward the site of forceps fixation during puncture.

c For the counterpuncture, a knife with a rounded back may be directed straight toward the forceps since the tip will deviate and emerge alongside the forceps (see Fig. 5.44a). *Note:* The tip is aimed about 1 mm higher to allow for refraction (see Fig. 5.37).

d The section is initiated by a sweeping motion of the blade, with the initial puncture site as pivot point (*red circle*). The cutting edge is guided so that the vectors of maximum tissue resistance are directed toward the site of forceps fixation.

e Completing the section: The blade is moved away from the fixation forceps



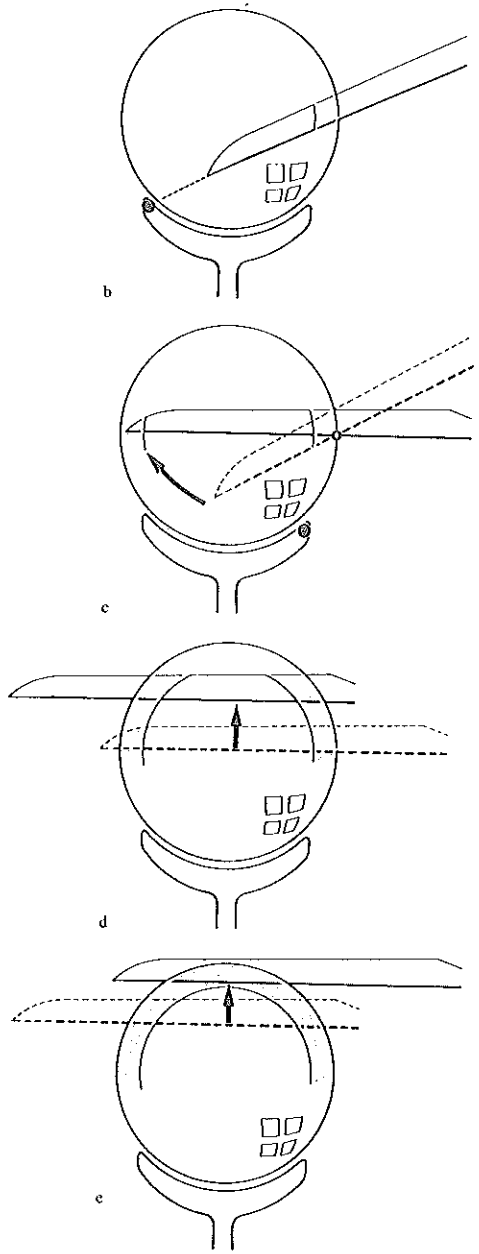


Fig. 5.46. Cataract knife section with fixation from below (favoring the sectioning maneuver)

a Principle: The vectors of puncture and counterpuncture are directed through the application site of the forceps.

b The puncture is directed toward the fixation instrument. Knives with a straight back make it easier to maintain the initial direction of insertion (see Fig. 5.44b). If broad fixation forceps are used, the tip is directed toward the far end (*red dot*).

c Counterpuncture is initiated with a sweeping motion so that the vector resisting the tip motion passes through the site of forceps application. The wider the forceps jaws, the smaller the necessary angle of the sweep, so the guidance of the knife approximates that for lateral fixation.

d, e Section is completed by a to-and-fro motion of the blade

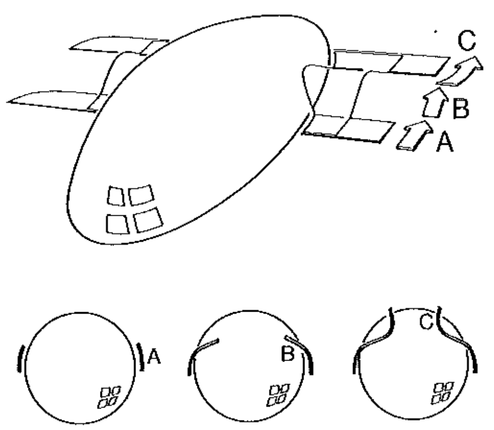


Fig. 5.47. **Corrective movements of the cataract knife.** The shape of the incision depends on the geometric intersection of the guidance path with the corneal dome. If the blade is not directed parallel to the iris (*A*), the incision will turn inward if the plane of the blade is raised (*B*) or outward if it is lowered (*C*)

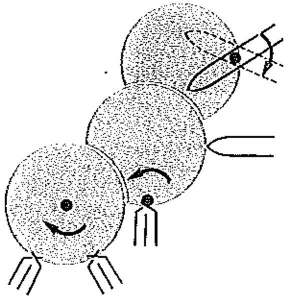


Fig. 5.48. **Centers of rotation for actions associated with the cataract knife section.** The center of rotation for corrective movements of the fixation forceps (see Fig. 3.21a) is at the center of the globe (*bottom*). Movements of the knife (see Fig. 3.21b) rotate the globe about the application site of the forceps (*center*). Swiveling movements of the knife (see Figs. 5.45d and 5.46c) should pivot at the puncture site to prevent the escape of aqueous (*top*)

Since the puncturing and sectioning maneuvers are separate with this instrument, both vectors cannot be simultaneously opposed by a single *fixation*. Therefore the surgeon must decide whether main resistance should be given to the puncturing vector or the sectioning vector. This will determine whether the fixation instrument is applied opposite the puncture site or opposite the end of the incision (Figs. 5.45, 5.46).

Broad fixation forceps allow greater freedom in this regard. However, they can also cause tissue distortion (very critical in this technique) unless they are held exactly in the position predefined by the shape of the grasping surfaces.[22]

Loss of aqueous can be prevented only during the puncture and counterpuncture. As soon as the section is begun, the incision is made under more demanding conditions, i.e., with lax tissue, decreased sharpness, and a protruding diaphragm. To avoid iris injury, the surgeon should pass the knife beyond the pupil margin immediately after making the counterpuncture, while the chamber still has sufficient depth. He must avoid any corrective maneuvers prior to this, because any tilting, raising, dipping, or withdrawal of the blade will allow premature aqueous escape. Only after the knife has passed the pupillary margin the direction of the cut may be revised. It should be noted, however, that any *direction change* in the incision will also change the *width* of the opening (Fig. 5.47).

The cataract knife section requires considerable skill, because the movements of the fixation forceps, knife, and the relative movements between them have *different centers of rotation* (Fig. 5.48). A good result is obtained only if these movements are perfectly coordinated at all times. This is made difficult by the requirement that all movements be performed swiftly and smoothly in the initial phase, i.e., before the blade passes the pupil margin.

5.4.3 Cutting with a "Point" Cutting Edge

Keratomes, cataract knives, and other broad-bladed knives are designed for making incisions in a *single plane*. To produce more *complex* incisions, techniques are required that immerse only a very small blade width in the tissue (see Fig. 2.74). The blade will then behave more or less as a "point" cutting edge and can be directed as needed to produce incisions of any shape desired (Fig. 5.49; see also Fig. 2.66).

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[22] Deformation by wide grasping forceps as illustrated in Fig. 3.20b is a particular problem when the anterior chamber has emptied and the now "blunt" cataract knife tends to push the tissue aside rather than cut it.

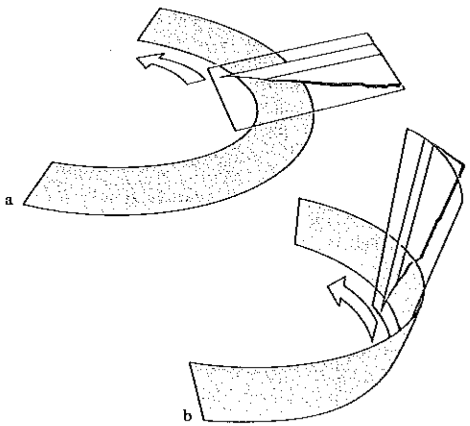

Fig. 5.49. **Opening the anterior chamber with a razor blade.** The technique of holding and guiding the blade determines the profile of the resulting incision.

a Coronal incision is made by guiding the blade on one plane, imitating a cataract knife or keratome section (preparation for continuing the section with scissors as in Fig. 5.55a).

b Perpendicular incision is made by holding the blade upright and guiding it along a conical surface (preparation for scissor section as in Fig. 5.55b)

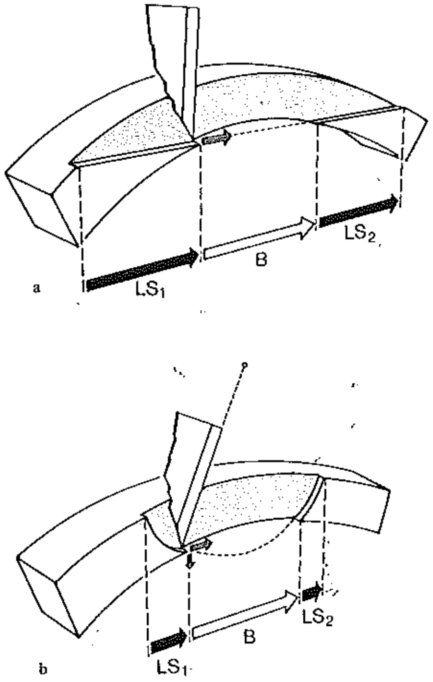

Fig. 5.50. **Avoiding centripetal vectors on opening the anterior chamber with a long incision using a razor blade fragment**

a An interior opening of specified length (*B*) can be made by a purely tangential blade motion. The cut is started some distance from *B* so that the blade first passes through an intramural "lead segment" (*LS*) before incising the deep surface of the cornea. As a result, the external opening is longer than the internal opening.

b If the incision is started closer to *B* (shorter *LS*) to reduce the length of the external opening, the blade motion will inevitably produce centripetal vector components

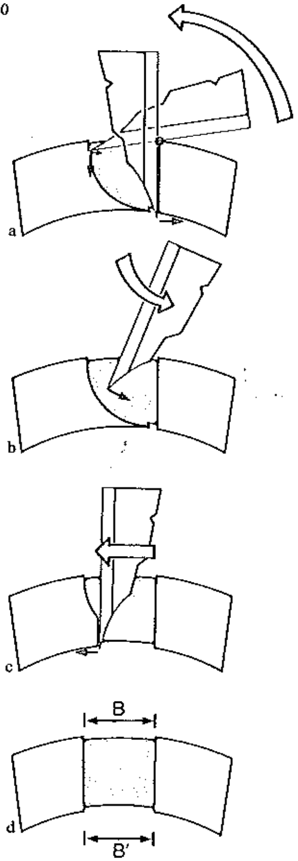

Fig. 5.51. Avoiding centripetal vectors on opening the anterior chamber with a short incision using a razor blade fragment

a When the intent is to make an incision that has equal external and internal lengths, centripetal vector components can be reduced by rotation of the blade. Centripetal vectors then exist only as long as the blade is within the tissue. The moment the chamber is entered, only tangential vector components are operative.

b For extending the incision the blade is removed, turned 180°, and reintroduced into the wound with the blunt edge leading.

c Then the blade is moved tangentially until the deep wound length matches the superficial wound length.

d Result: $B = B'$; no lead segment

However, a blade used in this fashion cannot seal the incised opening, and most of the incision must be made with the chamber opened, and thus with decreased tissue sectility. This places very high demands on the cutting ability of the instrument. Even with a very sharp blade, though, only a short chamber opening can be made unless the tissue resistance is extremely low.[23]

Because the anterior chamber can empty, blade movements with centripetal vector components (i.e., directed toward the chamber) are hazardous in this technique. These components are avoided by guiding the blade *strictly in a tangential direction* (Figs. 5.50a, 5.51c).

5.4.4 Scissor Section

Scissors can accurately cut tissues of low sectility, so they are used to *complete the cut* after the anterior chamber has been opened with another instrument. Scissors also allow a *safe section* because the "danger zone" (see Fig. 2.81b) is precisely defined, and its size can be reduced by taking small bites with the scissors.

An important safety factor is the *tangential movement* of the cutting point during the section (Fig. 5.52b).

Real danger exists only during **insertion of the scissor blades** into the anterior chamber, when *centripetal* vectors are unavoidable (Fig. 5.52a). That is why, in corneal scissors, the end of the inserted blade is rounded to prevent inadvertent tissue lesions (Fig. 5.53a). Also, the rounded blade is longer so that it will not slip out of the chamber when the scissors is closed (Fig. 5.53b). An incision of constant profile is obtained by cutting in opposite directions with *two scissors*, each a mirror image of the other (Fig. 5.54).

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[23] E.g., the incision of a deep precut groove, where only a very thin layer remains to be divided before entering the chamber.

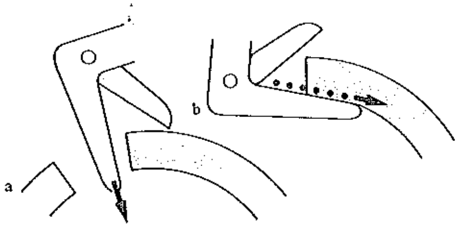


Fig. 5.52. Force vectors produced by scissors

a Centripetal vectors occur when the blade is introduced into an opening.

b During the scissor section, the vector of the cutting point motion is parallel to the surface

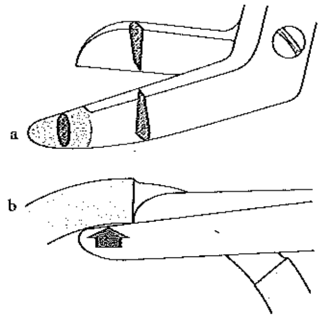


Fig. 5.53. Special design features of corneal scissors: Blade tips

a If the blade inserted into the chamber is blunt-tipped and well rounded, it forms a kind of spatula (*gray*) that projects past the ground edges of the blades. *Red*: Cross-sections of the cutting and blunt blades.

b The longer inner blade keeps the scissors from slipping out of the eye upon closure

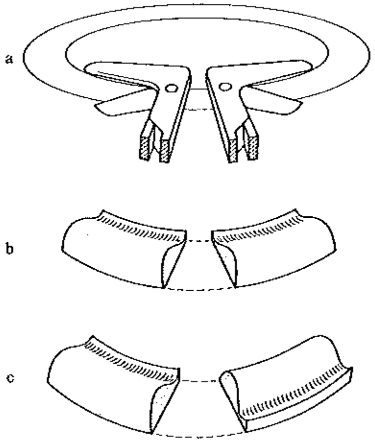


Fig. 5.54. Special design features of corneal scissors: Arrangement of blades. Identical, S-shaped cut profiles are obtained by cutting in opposite directions with two scissors, each a mirror image of the other.

a Mirror-image scissors for bidirectional cutting.

b Continuous profile (see also Fig. 2.79) obtained with mirror-image scissors.

c Discontinuous profile made by using a single scissors to cut in both directions

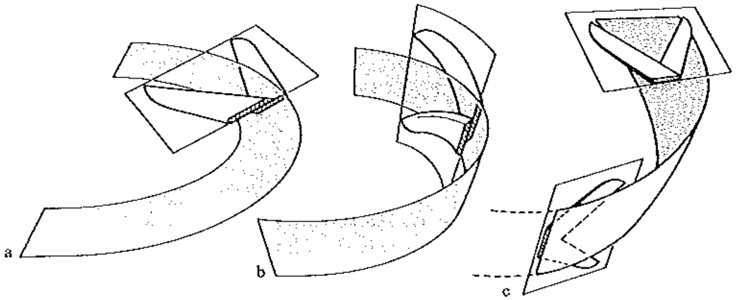


Fig. 5.55. **Relation between the shape of the scissor blades and the shape of the resulting cut.** If the blade shape is consistent with the desired shape of the cut (i.e., the guidance path is congruent with the cut surface), the cut can be completed by simple closure of the blades.

a Straight blades are suited for making flat cuts parallel to the iris.

b Perpendicular cuts are made with blades whose curvature conforms to the conical surface of the cut.

c The plane of the cut can be varied by changing the inclination of the scissors. In this example the ends of the incision are rotated 90° relative to each other. This facilitates opening the wound through rotation of a flap because hinge formation can occur without intramural alignment, i.e., with minimum distortion of surrounding tissue (see Fig. 1.51c)

The curvature of the scissor blades should conform to the shape of the planned incision (Fig. 5.55). If this is the case, the section can be completed with a minimum of swiveling movements (Fig. 5.56c). The main concern in the scissor section is to keep the *iris* away from the interblade "danger" zone. Thus, the blades are opened only slightly when initiating the cut to ensure that the enclosed corneal tissue will obstruct access to this zone (Fig. 5.56a). The depth of insertion can be limited by bracing the outside blade against the corneal surface. The inside blade is pressed firmly against the inner corneal surface to prevent incarceration of underlying tissues (Fig. 5.56b).

Safety can be enhanced by introducing *viscoelastic material* to displace the iris backward before enlarging the incision with the scissors; this creates additional room for inserting the scissor blade and for the following maneuvres.

The safety of the iris can be checked directly by watching the blades or indirectly by watching for concomitant pupillary motion (Fig. 5.57).

Disadvantages of the scissor section are the high cutting resistance and the complicated profile of the section. Both correlate with the tissue thickness, however, and are minimized by *preliminary thinning of the tissue layer* (see Fig. 2.80d).

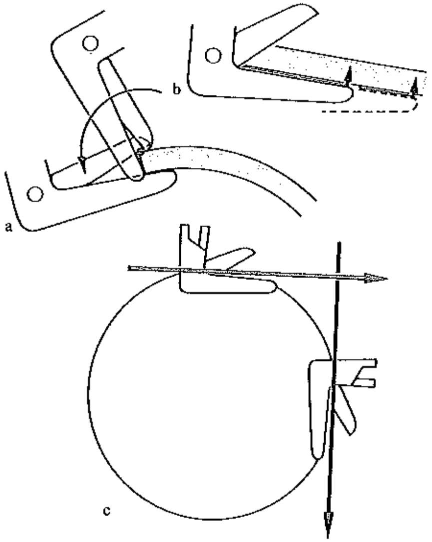


Fig. 5.56. **The scissor section**

a Introducing the scissors: The blades are nearly closed when introduced to avoid injury to intraocular structures. An aperture just large enough to accommodate the corneal thickness will safely obstruct access to the interblade area. The outside blade is braced against the outer corneal surface to prevent inadvertent deep entry into the chamber. Then the instrument is rotated about the outer blade tip into the chamber (*red dot*: Pivot point).

b Extending the cut: The inner blade is apposed firmly to the deep corneal surface to guard against iris incarceration.

c Guiding the scissors: To keep the cutting point moving tangentially to the limbus at all times, a 90° direction change is required through each quadrant. If this is not guaranteed by the blade curvature, the handle must be moved in a wide arc during the section

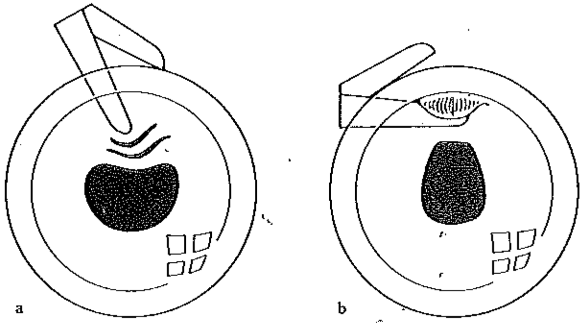
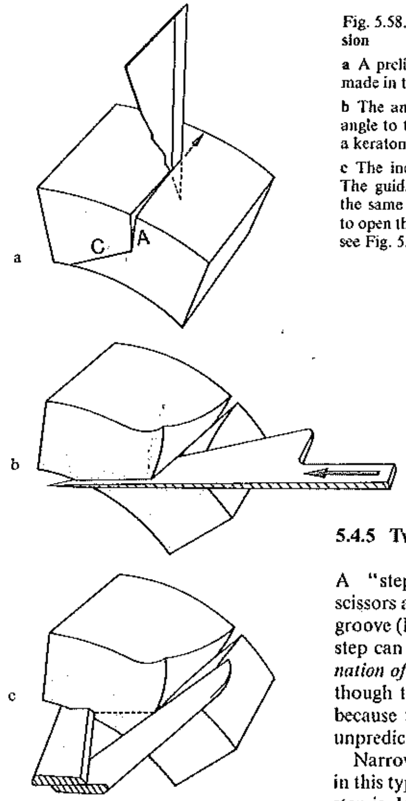


Fig. 5.57. **Monitoring the iris during the scissor section.** Distortion of the pupil is a sign that the iris has been caught by the blades.

a Inward displacement of the iris on insertion of the inner blade (→ iridodialysis).

b Outward movement of the pupillary margin indicates incarceration of iris between the blade and cornea (→ iridectomy)



5.58

Fig. 5.58. **Technique of the two-step incision**

a A preliminary perpendicular incision is made in the sclera (*A*) (cf. Fig. 5.4).

b The anterior chamber is entered at an angle to the precut groove (*C*) (here with a keratome).

c The incision is enlarged with scissors. The guidance path of the scissors is on the same plane as that of the knife used to open the chamber (b) (here: Horizontal, see Fig. 5.55a)

5.4.5 Two-Plane Stepped Incision

A "step" is created whenever scissors are used to enlarge a precut groove (Fig. 5.58). The width of the step can be controlled by the *inclination of the scissors* (Fig. 5.59), although this control lacks precision because the tissue tends to shift in unpredictable ways.

Narrow steps cause few problems in this type of incision. But if a wide step is desired, the tissue resistance will rise with increasing step width (see Fig. 5.36c).[24]

5.4.6 Three-Plane Stepped Incision

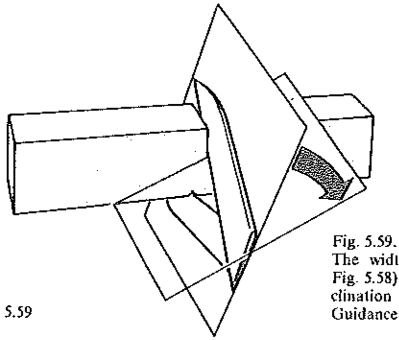
In this incision the resistance to entering the anterior chamber is independent of the step width. The intralamellar portion of the steps is formed in a separate phase (Fig. 5.60). It can be made as wide as desired and placed at any depth.[25]

When the chamber itself is entered, perpendicular vectors (directed toward the eye interior) can be avoided by tenting the inner lamella with forceps (Fig. 5.60c) and then sectioning it with a purely "tangential" guidance motion.

The width of the step is controlled by varying the guidance direction (Fig. 5.61), not by the inclination of the cutting instrument as in the two-plane incision. Therefore cutting can always be done on a vertical, where tissue resistance is lowest.

Corrections are easily made as the three-plane incision is carried out. Small irregularities (Fig. 5.62) usually cause no harm. A serration in the course of the surface groove can even provide a helpful landmark for approximating the wound margins. Variations in the step width also cause few problems. Associated changes in the margin of watertightness can be compensated by appropriate suture placement according to the hinge rule (see Fig. 5.28).

The mutual independence of the outer and inner wound margins in the three-step incision (cf. Fig. 5.35b) can be utilized to achieve specific goals. For example, the outer wound margin can be configured for optimum closure while the inner wound margin is adapted to anatomic conditions (Fig. 5.63).



5.59

Fig. 5.59. **Changing the width of the step.** The width of the step (segment *C* in Fig. 5.58) is controlled by changing the inclination of the cutting instrument (*red*: Guidance path of the blades)

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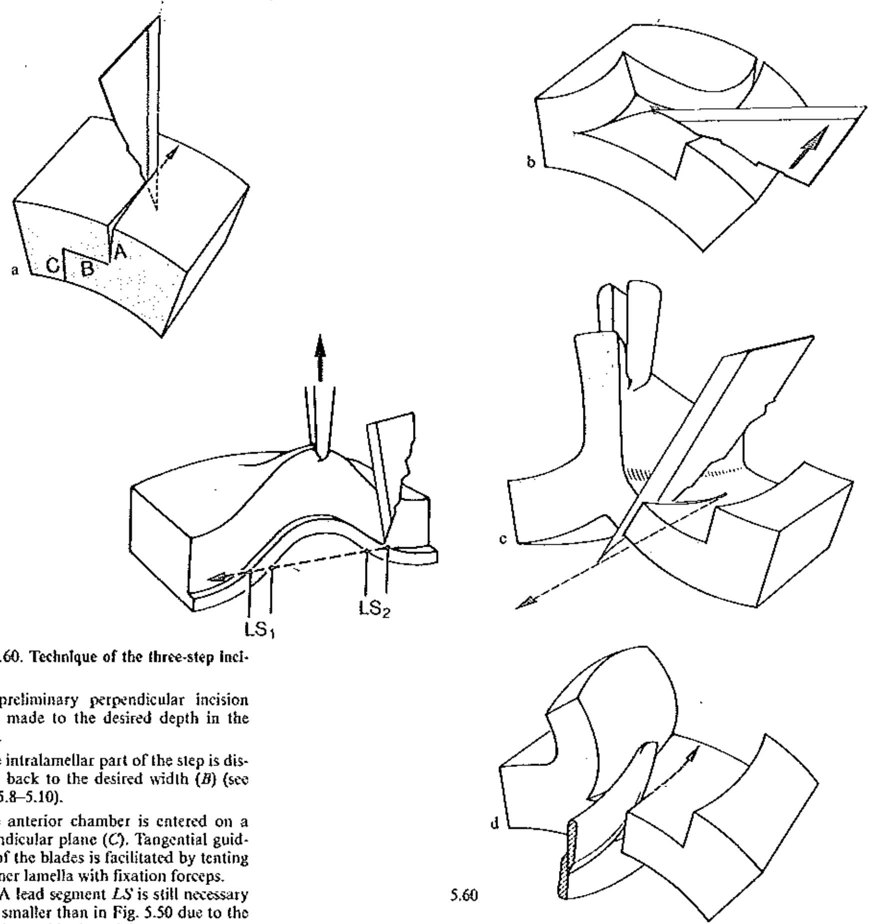
[24] *Note:* Scissors held at an oblique angle carry a risk of desquamating the corneal endothelium and Descemet's membrane.

[25] The step may be placed so deep that the inner lamella is transparent and affords a direct view into the chamber periphery.



5.60

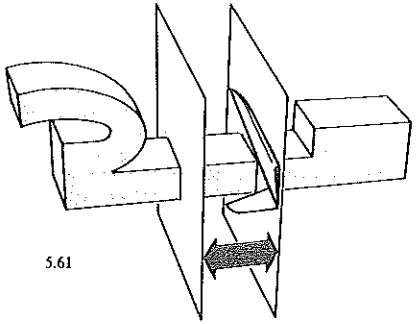
Fig. 5.60. **Technique of the three-step incision**

a A preliminary perpendicular incision (*A*) is made to the desired depth in the sclera.

b The intralamellar part of the step is dissected back to the desired width (*B*) (see Figs. 5.8–5.10).

c The anterior chamber is entered on a perpendicular plane (*C*). Tangential guidance of the blades is facilitated by tenting the inner lamella with fixation forceps.
Left: A lead segment *LS* is still necessary but is smaller than in Fig. 5.50 due to the preliminary thinning of the cornea.

d The incision is enlarged with scissors. Their guidance path is perpendicular (see Fig. 5.55b)



5.61

Fig. 5.61. **Controlling the step width.** The step width is changed by shifting the cutting instrument laterally, i.e., toward the limbus or toward the corneal center as needed (*red*: Guidance path of the cutting edge)

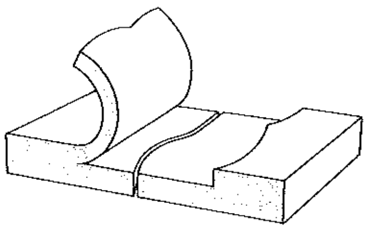


Fig. 5.62. **Irregularities in the stepped incision.** Irregularities in the course of the incision do not hamper wound closure as long as the valvular mechanism remains intact

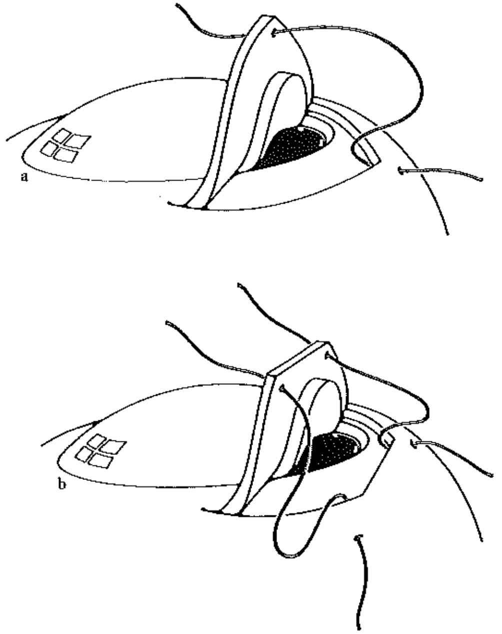


Fig. 5.63. **Disparities in the shapes of the external and internal wound margins ("gothic arch" incision)**

a The *external* wound margin consists of two intersecting segments of great circles and can be closed with one suture at the apex (see Fig. 5.31d and e). The *internal* wound margin parallels the limbus to respect the local anatomy.

b Incision with a truncated apex: The external wound margin consists of three smaller segments, all of which are closed with only two preplaced sutures. This type of incision allows the insertion of instruments or implants through one segment while the others remain safely closed

5.4.7 Trephine Incisions

Trephines are circular blades (Fig. 5.64) that excise round tissue pieces of precisely defined *diameter* and edge *profile*. In theory, a given trephine should excise perfectly congruent disks from different eyes,[26] but in reality trephine incisions show individual variations, and specimens cut from different eyes do not have identical shapes. The *discrepancies* are caused by tissue displacements that stem from asymmetrical resistances. Yet the greatest discrepancies occur when the incision is started with a trephine and completed with a different instrument.

If the anterior chamber empties the moment it is opened, the iris and lens will move forward against the cutting edge of the trephine, making it necessary to discontinue the trephination. Continued use of the trephine after opening the anterior chamber requires means to prevent the escape of aqueous. A *no-outflow system* is established either by using a self-sealing instrument design (Fig. 5.65d) or by first replacing the aqueous with viscoelastic material (see Fig. 1.4c).

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[26] Absolute congruity is essential for optimum corneal grafting, because discrepancies between donor and recipient are a source of irreversible astigmatism.

Fig. 5.64. **Manual trephines**

a Effect of handle diameter on cutting excursion. The handle circumference determines the number of revolutions made by the trephine when rolled between the fingers. The two trephines shown have the same cutting diameter (*A*), but the trephine with the smaller handle radius (*B*) completes more turns (=greater pull-through action) when rolled than the thick-handled instrument.

b When rotated, the trephine is rolled along the fingers. Its position is unstable, since the trephine has a tendency to travel, but this instability is partially compensated by the high lateral resistance of the blade

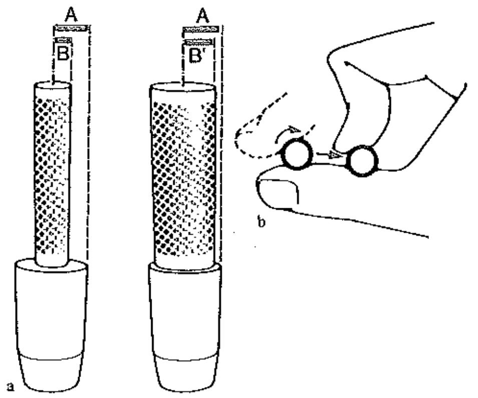


Fig. 5.65. **Open trephines and trephines with a central plunger**

a Open trephine with no depth stop. The operative field is visible through the opening.

b Trephine with an inner plunger. The plunger acts as a stop to limit the depth of the cut (e.g. for lamellar keratoplasty).

c In a penetrating keratoplasty, the stop prevents the cutting edge from passing too deeply.

d The stop serves to seal the aqueous space and prevents emptying of the anterior chamber when trephining an irregularly arched cornea

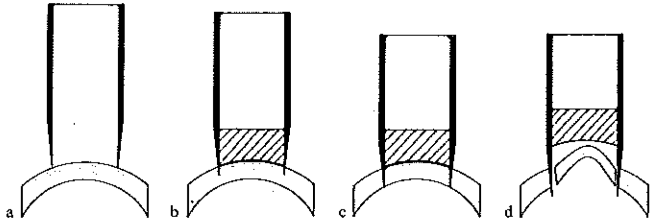
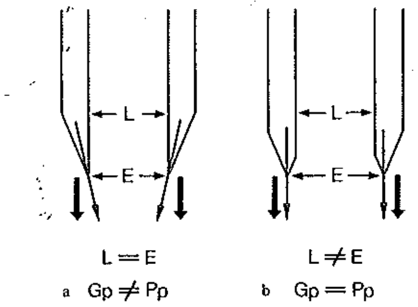


Fig. 5.66. **Bevel of the cutting edge.** The bevel angles of the trephine blade are critical for blades of finite thickness because any discrepancies between the preferential path (*red arrows*) and guidance path (*black arrows*) result from the instrument design and cannot be corrected by manual guidance.

a Bevel only on the outside edge. Inside, the diameter of the bore (*L*) equals the diameter at the cutting edge (*E*). The preferential path (the line bisecting the cutting edge, see Fig. 2.73) does not coincide with the guidance path, so an asymmetric lateral resistance develops.

b Counterbevel on the inside edge. The preferential path and guidance path coincide. The inside diameter at the cutting edge is slightly greater than the bore diameter, so tissue entering the hollow of the instrument is slightly compressed.

P_p: Preferential path
G_p: Guidance path



Cylindrical Trephines

Open cylindrical trephines (Fig. 5.65a) allow *visual monitoring* of the trephined disk through the hollow of the trephine. But the cutting edge itself cannot be seen at one time around the whole circumference of the blade due to the cylindrical shape. Open trephines cannot prevent aqueous leakage.

Trephines with a central plunger. A plunger provides an adjustable stop for controlling the depth of penetration (Fig. 5.65b)[27] and can produce a watertight seal.[28]

The **trephining motion** can be divided into two vector components: one perpendicular to the tissue surface (thrust) and one parallel to the tissue surface (rotation). The *thrust vectors* deepen the cut. The *rotation vectors* create a pull-through action that enhances the "sharpness" of the cutting process (Fig. 5.70). The *resistance* to trephining depends on which parts of the trephine come in contact with the tissue, and changes with the depth of penetration (Figs. 5.67–5.69). The interplay of forces and resistances is such that the action of the trephine on the disk and on the surrounding cornea is different. Also, the different forces and resistances vary in the phases *before* and *after* the anterior chamber is entered.

In the initial phase **before the chamber is entered** (i.e., during division of the parenchyma), resistances are distributed evenly along the circumference of the blade. Initial resistance to the trephining depends on the resistance to the cutting edge. As the cut deepens, lateral resistance increases and helps to *stabilize the guidance* of the trephine. Thus, the precision of the trephine incision improves as the blade penetrates deeper into the tissue, and the amplitude of the cutting motion may be gradually increased as the incision proceeds. Even manual trephines (Fig. 5.64) can be guided with precision owing to the high lateral resistance that develops. Due to the high lateral resistance, the operator cannot redirect the incision once the cut has been initiated, so the result depends entirely on the inherent *cutting characteristics of the instrument* (Fig. 5.66).[29] In the thrusting mode lateral resistances are asymmetrical, and *lamellar deflection* may shift tissue toward the trephine opening (Fig. 5.71a).[30] This deflection can be minimized by reducing the thrust vector (applying gentle pressure) and making the cut chiefly by rotation of the trephine.

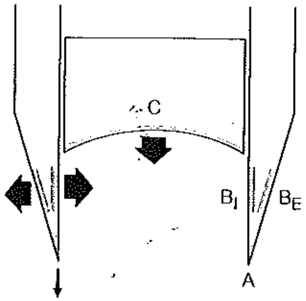


Fig. 5.67. **Design-related sources of resistance in trephines**

A Cutting resistance develops at the sharp cutting edge. The main component acts in the direction of thrust.

B Lateral resistance develops at the lateral surfaces of the cutting edge. Its effects depend on tissue displacement and hence are greater outside the hollow (B_E) than inside (B_I).

C Additional resistance develops if the central plunger meets the corneal surface. This resistance affects only the trephine disk

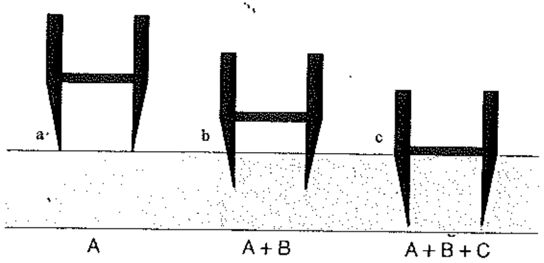


Fig. 5.68. **Effect of penetration depth on resistance prior to entering the anterior chamber**

a Application of the trephine. Only the cutting resistance (*A*) is operative at this stage.

b Penetration of the parenchyma. Lateral resistance (*B*) becomes an increasing factor with increasing depth of penetration.

c Maximum penetration. Contact between the plunger and cornea creates an additional resistance (*C*)

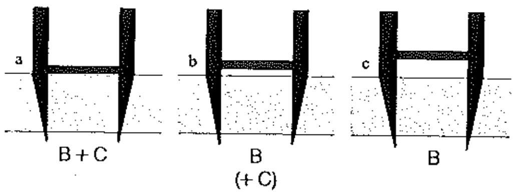


Fig. 5.69. **Effect of plunger position following entry into the anterior chamber.** Once the cutting edge enters the chamber, cutting resistance (*A*) is no longer a factor.

a Depth of plunger set exactly at corneal thickness: When the chamber is entered, the plunger resistance at the disk (*C*) is added to the lateral resistance (*B*).

b Plunger set slightly deeper than corneal thickness: The moment the chamber is entered, the plunger has no contact with the cornea. Concomitant rotation of the corneal disk is determined only by lateral resistance. Fluid pooling beneath the plunger acts as a lubricant; it may transmit some rotation of the plunger to the cornea, depending on its rheological properties.

c Plunger set much deeper than the corneal thickness: There is space over the cornea to allow for folding of the disk

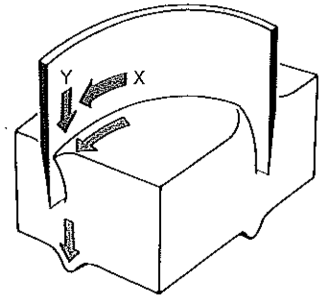


Fig. 5.70. **Vector components of the trephine section.** The perpendicular components (*Y*) cause the cut to progress in depth. They also shift the tissue toward the anterior chamber. The components parallel to the surface (*X*) cut the tissue by an ("infinite") pull-through action. They also cause concomitant tissue motion in the direction of blade rotation

The rotation induces an entrainment of the tissue in the *direction of rotation* of the trephine. Fixation of the globe with forceps will eliminate this concomitant tissue motion outside the trephine, but it has no effect inside the trephine, where *shear effects* develop in the tissue between the outer cornea and the trephined disk (Fig. 5.72). These shear forces can shift tissue ahead of the blade and create irregularities in the lateral surface of the disk.[31]

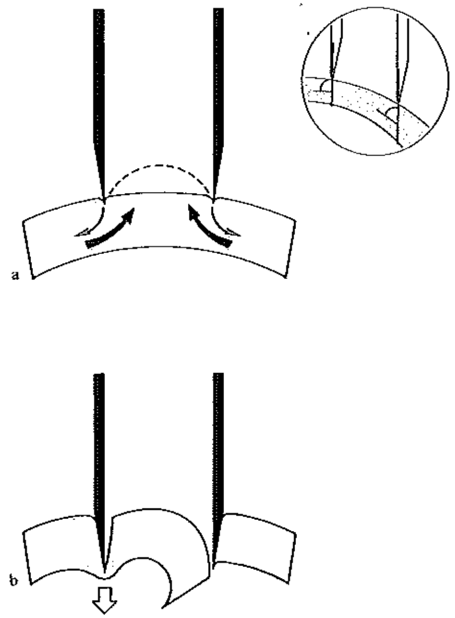


Fig. 5.71. **Tissue motion accompanying blade thrust**

a In the phase before the anterior chamber is entered, the cut may deviate as a result of lamellar deflection. The extent depends on the bevel of the cutting edge (i.e., the direction of the preferential path; see Fig. 5.66) and the angle of attack on the lamellar surfaces (which in turn depends on the site of application on the corneal dome, i.e., the diameter of the trephine; see *inset*).

b In the phase after the chamber is entered, the trephine blade tends to push ahead the still unsectioned tissue. Because these tissue layers have become lax and less sectile, it is difficult to divide them with the trephine

In the second phase, **after the anterior chamber is entered,**[32] the situation changes drastically: The tissue becomes less sectile, and the

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[27] Visual monitoring of the disk is possible only from inside the eye using an endoscope. Experimental endoscopic studies form the basis for the following analysis of the trephining process.

[28] The seal must not be airtight, however, because if air is trapped between the blade and cornea, penetration becomes impossible. To avoid airtightness, the bore must be dry before the trephine is applied to the cornea. Otherwise fluid residue may obstruct air outflow.

[29] That is why the same trephine should be used to obtain congruent disks from different eyes.

[30] The extent of the deflection depends on the intraocular pressure and is greater at low pressures (=low tissue sectility). Therefore donor and recipient eyes should be trephined at equal intraocular pressures to obtain congruent disks.

[31] Shear effects can be reduced by applying a friction-reducing lubricant, i.e., by moistening the corneal surface. But note: The fluid should be applied to the corneal surface *after* the trephining is started. Otherwise it will enter the hollow of the trephine and trap air (see footnote [28], p. 178).

[32] *Note*: The second phase requires a no-outflow system, that means trephination with a watertight plunger or visco-elastic stabilisation of the anterior chamber.

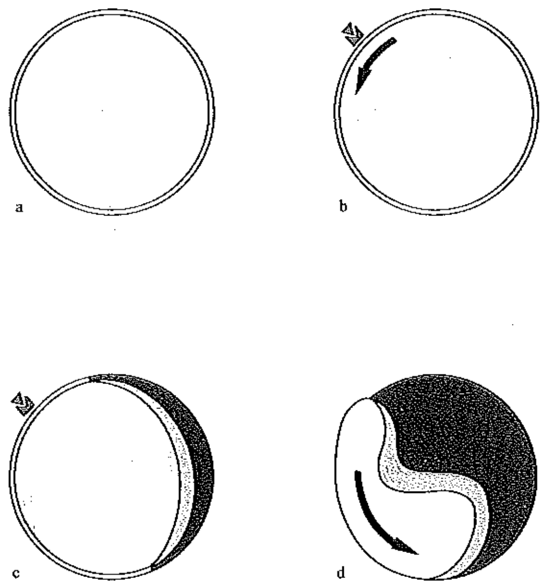

Fig. 5.72. Tissue motion accompanying blade rotation

a The drawing shows the position of the corneal disk in the resting state (i.e., at the moment the stationary trephine is applied). This position is marked by imaginary cross-hairs to allow comparison with later drawings.

b During penetration of the parenchyma, the tissue is entrained by the rotating blade. If the peripheral cornea is fixed by forceps at this stage, only the tissue inside the trephine will be twisted. This creates shearing motions between the lamellae in the (superficial) part of the disk already divided and the (deep) portions of the cornea not yet divided.

c After the anterior chamber is entered, the divided part of the disk becomes more mobile and is driven toward the portion still attached.

d When more than half the disk has been excised, it may become folded if there is sufficient space in the hollow of the trephine.

▧ site of forceps application

thrusting motion of the blade tends to push the still undivided corneal lamellae ahead, preventing a full-thickness excision (Fig. 5.71b). Moreover, the distribution of resistances along the circumference of the blade becomes unequal, and with rotation of the blade the divided, mobile portion of the disk tends to rotate toward the portion that is still attached. This results in a folding of the partially excised disk, and the cutting process continues in deformed tissue (Fig. 5.72c, d). Yet, as the undivided portion becomes twisted and stiffened, its sectility is restored, and a full-thickness trephine incision may be completed. At that point the corneal disk flattens out again within the hollow of the trephine because the resistances along the circumference of the blade again become uniform. But though apparently the disk has been excised smoothly with one precise cut, it does not have the ideal cylindrical shape because of the tissue distortions occurring in the final phase of the cut.[33]

Trephines with a Pointed Blade

Constant, complete *visual monitoring* of the trephination is possible only with the use of a *cone-shaped* instrument. The basic design requires a pointed blade that travels along a conical outer sleeve (Fig. 5.73).

Small blades are extremely mobile owing to their low lateral resistance and can easily deviate from the intended path. It is more difficult to achieve a circular incision than with a cylindrical trephine, because the low lateral resistance cannot adequately stabilize the instrument. The cut may deviate laterally whenever the blade encounters a site of increased tissue resistance (Fig. 5.74). To avoid this, the trephine and cornea must be apposed so securely that the resistance to lateral deviation is greater than the force inducing the deviation.

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[33] These deformations are unnoticed by the surgeon because they are hidden by the plunger. The degree of these distortions depends on *friction*, i.e., on the area of contact between the trephine and tissue, and is greatest when the plunger of the trephine touches the corneal surface (see Fig. 5.69a). The friction is reduced by fluid escaping from the chamber and pooling beneath the plunger (Fig. 5.69b). Thus, if the chamber has been filled with viscous or viscoelastic material prior to trephining, their rheologic properties can be exploited for lubrication. However, these materials can transmit rotary motion from the plunger to the corneal disk, depending on their maximum viscosity at low shear rates (see Fig. 2.17). If *empty space* exists below the plunger the moment the anterior chamber is entered (Fig. 5.69c), there will be no plunger friction, but deformation of the disk is facilitated because the dead space makes room for folding or even inversion of the disk (Fig. 5.72d).

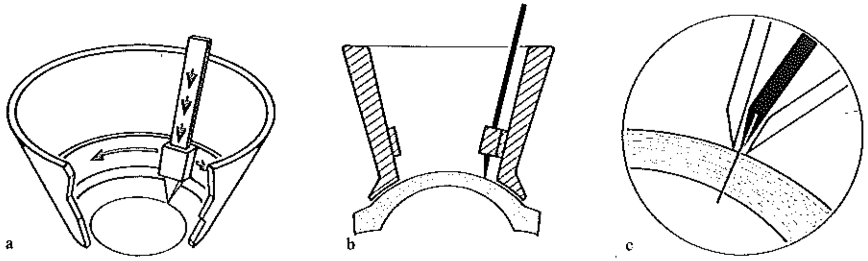


Fig. 5.73. Trephine with a pointed blade

a The point of the blade travels along a conical carrier as it is advanced more deeply. Both motions require precise mechanical control.

b Cross-section through the cone and blade.

c With cones of varying inclination, various angles of attack at the tissue can be selected

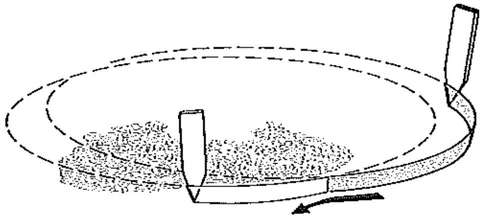


Fig. 5.74. Lateral shifting tendency of the trephine. The blade tends to bypass areas of increased resistance within the cornea, e.g. scars (*gray*). The carrier may shift relative to the corneal surface, or the globe may shift relative to the cone if the resistance to this shift is smaller than its force. In contrast to cylindrical trephines, then, the cut may deviate laterally (*red*) from the intended circular path (*black*)

Completion of the Trephine Section

Once the anterior chamber has been entered, trephining can be continued only as long as the chamber retains sufficient *depth*. If the corneal disk cannot be excised with the trephine alone, the section must be completed with a *scissors* or *ultrasharp blade*. But changing to a different instrument also changes the profile of the incision, and a ledge may be formed. Because this is a major source of *incongruity* between different disks, it is important to keep these ledges as small as possible. This is achieved by guiding a cutting edge precisely along the cut surface already established (Figs. 5.75, 5.76) and by minimizing tissue deformation in front of the cutting edge. *Scissors* (Fig. 5.77) are applied so that they distort only tissue that will subsequently be discarded (i.e., the residual cornea in the donor eye, and the disk in the recipient cornea). *Fixation instruments* are applied in a way that avoids traction that could deform or displace tissue in front of the cutting edge (Fig. 5.78).

If we analyze the trephining process, we find that the major obstacle to obtaining perfectly congruent disks is the tendency of the blade to *entrain or push aside the tissue*. This tendency results from the resistances that invariably develop along trephine blades of finite thickness. Thus, the key to improving precision with these instruments is to immobilize the peripheral cornea and corneal disk with methods that allow perfect fixation.

Best are "no touch" techniques that divide tissue without resistance, i.e., surgical lasers.

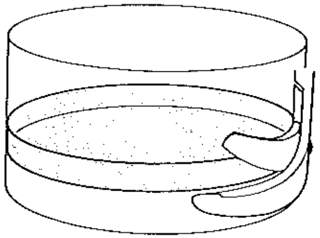


Fig. 5.75. **Completing the trephine section with scissors.** If the radius of blade curvature equals the radius of the trephine, the cutting point will follow the trephine incision on closure of the blades. Thus the blades make no swiveling motions in the anterior chamber

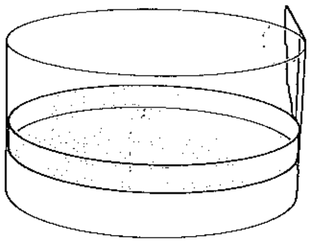


Fig. 5.76. **Completing the trephine section with a sharp-pointed blade.** The cutting edge of the blade is guided carefully along the edge of the corneal disk. It is held in the same plane as the trephine cylinder (i.e., vertically) and precisely follows the circular line of the trephine incision

5.5 Suturing the Cornea and Sclera

5.5.1 Suture Technique

Due to the unyielding nature of the tissue, extreme precision is required in the placement of corneal and scleral sutures.

The **needle track** is cut in lamellar tissue, so the *lamellar rule* applies. This means that the greatest accuracy is achieved when the needle tip is passed either parallel or perpendicular to the plane of the lamellae (Fig. 5.79) rather than obliquely (see also Fig. 5.2). This requirement is especially important in tissue with low sectility, which offers greater resistance to passage of the needle.

If tissue deformation is caused by the grasping forceps, it must be compensated for by appropriate countermovements during needle passage (Figs. 5.80–5.82).

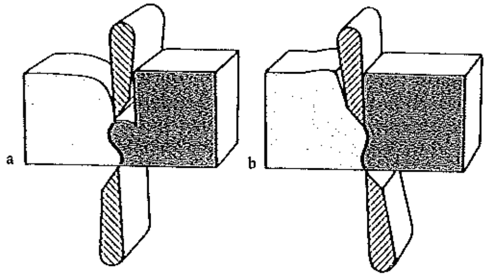


Fig. 5.77. **Completing the trephine incision with scissors** creates a step whose location is determined by the placement of the scissor blades. *Light gray*: Trephine disk, *dark gray*: Peripheral cornea.

a When the edge of the blade in the incision faces from the peripheral cornea toward the disk, the step forms in the peripheral cornea.

b When the cutting edge faces away from the disk, the step is formed in the disk

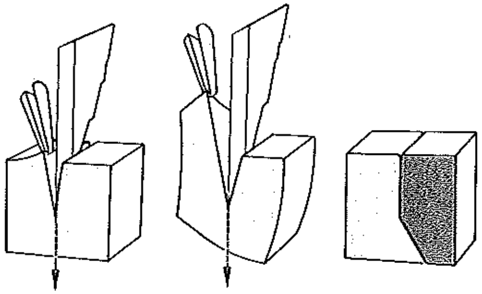


Fig. 5.78. **Step formation by traction with a grasping instrument.** If the forceps does not significantly deform the disk prior to cutting, the blade can make an almost step-free incision (*left*). But if the disk is stretched upward (*center*), an inverse step (=defect) may form in the peripheral cornea (*right*)

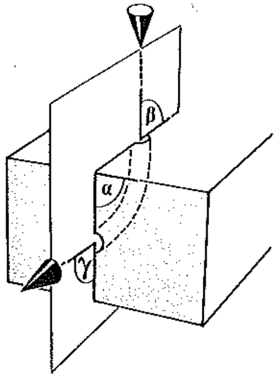


Fig. 5.79. **Suture characteristics.** A suture causes minimal shift of the wound surfaces when:

- the suture plane is perpendicular to the tissue surface ($\alpha = 90°$);
- the needle is inserted perpendicular to the tissue surface ($\beta = 90°$);
- the tip emerges perpendicular to the wound surface ($\gamma = 90°$)

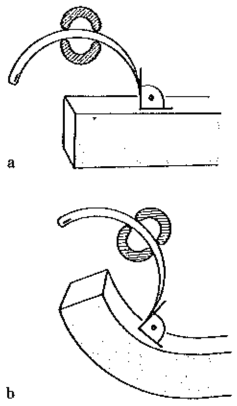


Fig. 5.80. **Inserting the needle perpendicular to the tissue surface**

a In an undeformed tissue surface, the needle shaft must be inclined well back to allow the tip to pierce the tissue at a right angle (note the position of the needleholder).

b If the tissue surface is picked up with a forceps, the needle position must be adjusted accordingly. The shaft may now be held in a more upright position

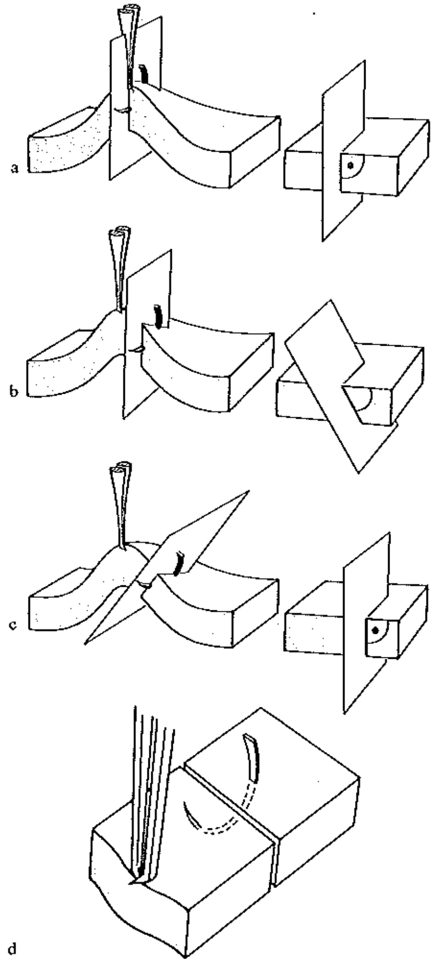


Fig. 5.81. **Obtaining a perpendicular suture plane**

Left: Tissue deformation by forceps.
Right: Position of suture plane after forceps release.

a–c The wound margin is picked up with a forceps to create resistance for suturing.

a If the needle is passed on the perpendicular plane directly beneath the forceps, the suture plane also will be perpendicular on release.

b The same maneuver performed at some distance from the forceps yields an oblique suture plane upon release.

c Compensatory slanting of the needle is necessary when the suture is passed at some distance from the forceps.

d An ultrasharp needle can be passed with very little fixation of the wound margins, so the forceps need not grasp (and deform) the tissue but merely touches its surfaces at the needle exit (see Fig. 2.40c). This eliminates the tissue deformation problems in **a–c**

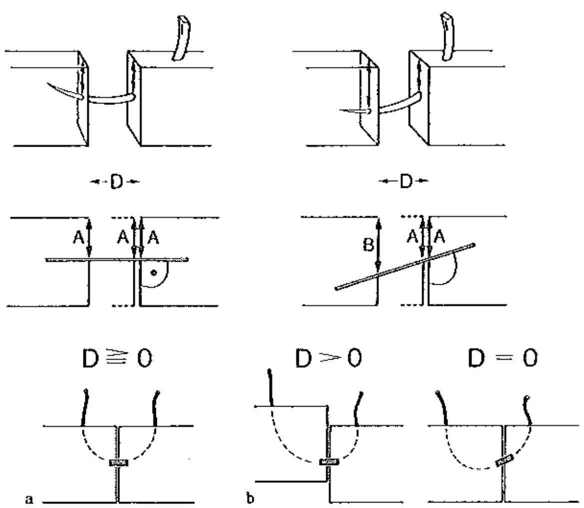


Fig. 5.82. **Effect of the direction of needle passage on wound apposition**

a Passing the needle parallel to the tissue surface results in equal suture depths in the two wound surfaces (*A*) regardless of the gap between them (*D*) at the time of suturing.

b Passing the needle obliquely results in different suture depths (*A* does not equal *B*), an effect that increases with the distance *D*. The degree of incongruity on tightening does not depend on the suture tension (*lower left*). If the wound margins are pressed together during oblique passage of the needle ($D=O$), the suture depths are equal ($A=B$), but the stitch is asymmetrical (*lower right*). The wound surfaces will remain apposed at low suture tension but will become incongruent when tension is increased

Loose sutures such as simple **apposition sutures** pose few problems because they do not alter the tissue topography. But *tight sutures* such as **compression sutures** shorten the suture track and cause deformations that may interfere with wound closure. The nature of the deformation can be inferred from the *rule of suture tightening* (see Fig. 2.100). In perpendicular incisions, the deep wound edges begin to gape when suture tension is increased (Fig. 5.83). In single-plane oblique incisions, the wound edges shift relative to each other and override (Fig. 5.84). In stepped incisions, superficial apposition is preserved but the valve mechanism is destroyed in the deeper portion of the wound (Fig. 5.85).

It should be noted that a *single deforming suture* can disrupt closure for the full length of the wound due to the rigidity of the tissue (Fig. 5.86, see also Fig. 5.94). This situation is best corrected by *removing* the offending suture. Any attempt to produce a countertension with "corrective sutures" would cause additional distortion that may restore watertightness, but at the cost of significant astigmatism.

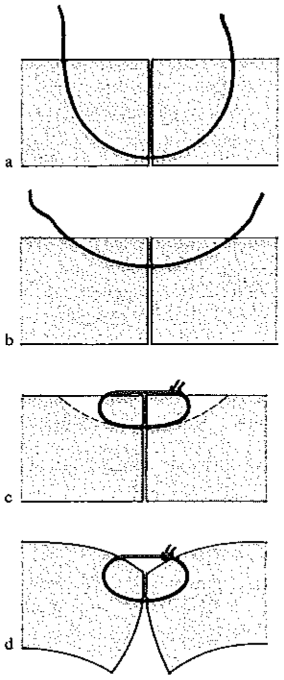


Fig. 5.83. **Suture problems in the perpendicular incision.** Comparison of sutures that enter and emerge at points equidistant from the wound line.

a A deep semicircular stitch produces a large compression zone. The depth of placement is limited by the tissue compatibility of the suture material (inflammatory canal, see Fig. 2.123).

b A superficial stitch compresses only a small part of the wound surface. Apposition in the deep (uncompressed) zone is maintained only if the suture track has not been shortened by tightening of the thread.

c The thin surface layer may tear when the suture is tightened. This places the suture closer to the wound line than planned.

d If the tissue does not tear, deep gaping occurs when the suture is tightened. Aqueous may rise to the suture track. Contrary to expectations, the more the suture is tightened, the greater the risk of fistula formation

Fig. 5.84. **Suture problems in the oblique incision** ►

a If the suture enters and emerges at sites equidistant from the external wound line ($A=B$), the stitch will be asymmetrical in the tissue and encompass little of the overriding wound margin.

b If the entry and exit sites are equidistant from the point of deep suture passage *D*, they will be asymmetrical on the tissue surface ($A>B$).

c When the suture is tightened, a vector component acts along the oblique incision to cause relative shifting of the wound margins (*inset*). The wound remains watertight, but apposition is faulty

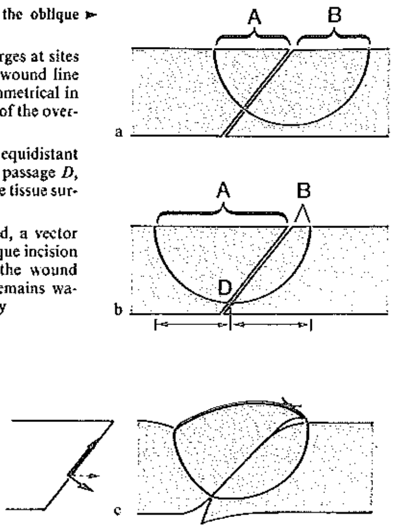
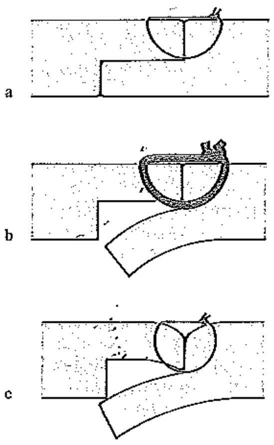


Fig. 5.85. **Suture problems in the step incision** ►

a The outer step is fixed by a superficial apposition suture and maintains the valve function.

b The valve mechanism is impaired by a thick thread in the interlamellar layer.

c The valve mechanism is also compromised by excessive suture tension. The entire valve is deformed and may leak



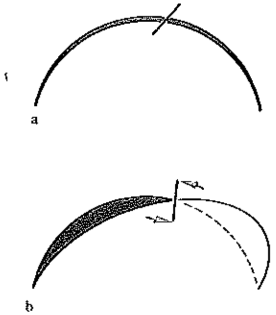


Fig. 5.86. **Tightening of obliquely placed sutures**

a When loose, an obliquely placed suture does not impair apposition.

b Tightening the suture causes the wound edges to shift, and leak occurs not just at the suture but along the entire wound line

5.5.2 Special Types of Suture

Given the difficulties that invariably occur when tight sutures are used in rigid tissue, it is best to avoid incisions that require compression sutures for effective closure (perpendicular incisions) in favor of incisions that can be made watertight with simple apposition sutures (valvular incisions).[34] In that case the type of suture used is far less important than the suture *length* – for any suture whose length exactly equals the length of the needle track makes a satisfactory apposition suture (see Fig. 2.97).

If the surgeon must deal with a *traumatic or irregular wound* of predetermined shape, he should seek the best compromise on the basis of the valve rule, hinge rule, and the rule of suture tightening.

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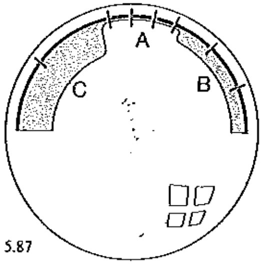
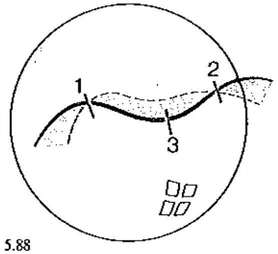
[34] Some very small valvular incisions can be made watertight simply by applying a contact lens.



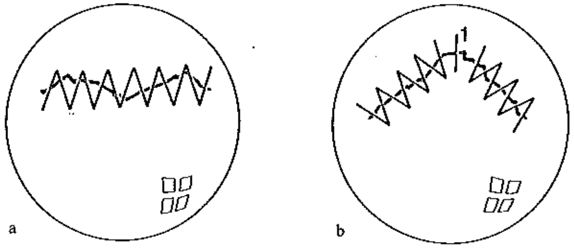
5.87

Fig. 5.87. **Wounds with a variable valve width.** Simple interrupted sutures are spaced according to the hinge rule. In segment *A* the wound surface is steepest (i.e., the valve is most narrow), so the sutures must be spaced closer together than in segment *C*, where the valve is very wide



5.88

Fig. 5.88. **Wound with valves facing multiple directions.** Simple interrupted sutures are placed at sites where the wound surfaces are perpendicular (*1* and *2*), subdividing the wound into segments whose valves face the same direction. These segments are managed according to the hinge rule (*3*)

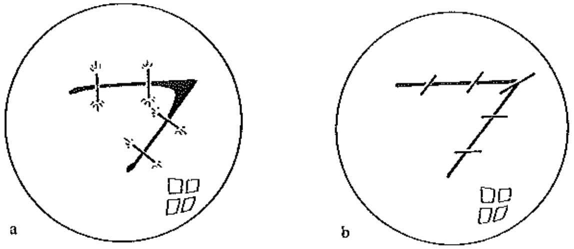


5.89

Fig. 5.89. **Continuous sutures on irregularly shaped wounds**

a Continuous sutures tend to linearize the encompassed area (see Fig. 2.103b). Thus the suture does not follow the irregularities in the course of the wound, but produces a linear compression zone that incorporates the entire wound area.

b If the wound line is too irregular to permit this, one or more simple interrupted sutures (*1*) are used to subdivide the wound into segments, which are then managed in accordance with a. (*Note*: Strong suture tension tends to flatten the corneal dome; see Fig. 2.103a)



5.90

Fig. 5.90. **Suturing a triangular flap**

a Compression sutures on the lateral wound margins would cause the apex of the flap to retract.

b Solution: The apex is sutured first. This is done by direct suture if sufficient tissue is present, i.e., if the flap angle is sufficiently large. The lateral sutures are placed obliquely to relieve tension on the apex

In incisions that have a **nonuniform valve width** (Fig. 5.87)[35] more sutures must be placed per unit wound length in portions with a narrow wound surface than in places with a wider valve. If the **plane of the cut is twisted** so that the valves face various directions (Fig. 5.88),[36] interrupted sutures can be placed at the nodes of the twist (i.e., at sites where the wound surfaces are perpendicular), subdividing the wound into *segments* that have a single valve direction. These segments are then closed according to the hinge rule.

Wounds with **multiple fine serrations** are best managed by dividing them into *subsegments* that can be closed with straight, continuous suture lines (Fig. 5.89).

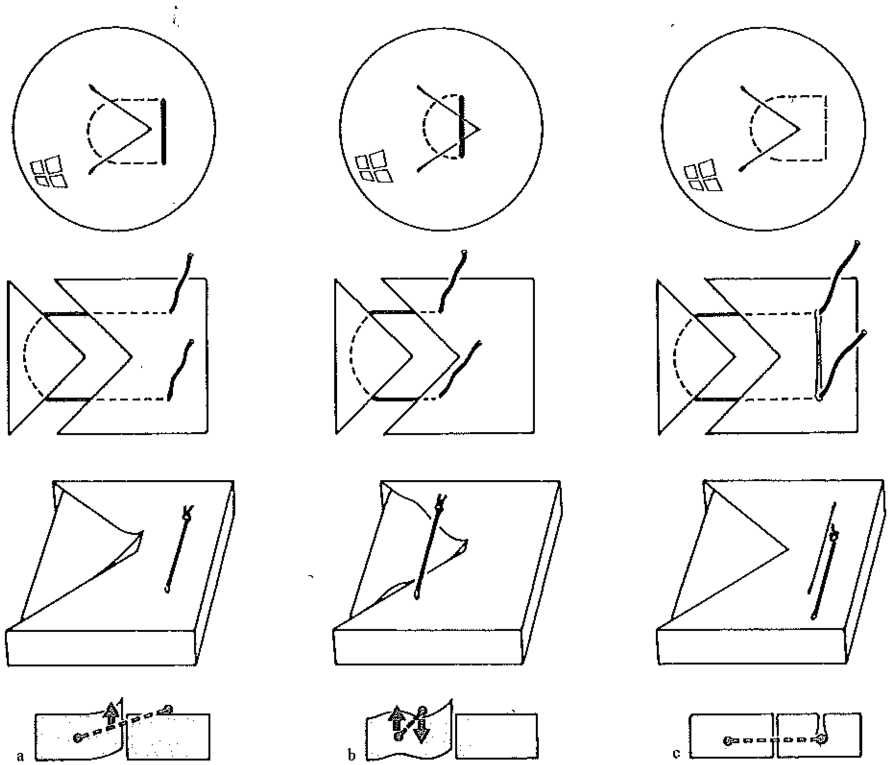


Fig. 5.91. **Closure of triangular wounds with intralamellar sutures.**
Top: View of the cornea from above.
Center: Semiperspective view of the loose and tightened suture.
Bottom: Cross-sectional view of the apical region.

a Partial intralamellar suture: The stitch is intralamellar in the flap and epicorneal distal to the flap. Tightening the loop creates vectors that evert the flap above the level of the cornea, forming a step.

b Passing the epicorneal part of the loop across the end of the flap (i.e., placing the suture less distally) creates vector components that press the flap downward and reduce eversion of the apex, although the surface of the flap is still somewhat irregular.

c For a purely intralamellar suture, the cornea is incised to the desired depth distal to the apex of the flap using an ultrasharp blade. The suture is passed from the base of this incision through the flap and back to the groove, affording a secure closure that keeps the flap flush with the surrounding cornea

The closure of **triangular and branched wounds** is especially challenging.[37] Compression of the side limbs causes immediate gaping of the apex (Fig. 5.90). The first step, then, is to *secure the apex*. If there is not enough tissue for a simple interrupted stitch, the apices can be apposed using *intralamellar sutures* (Figs. 5.91, 5.92). Sutures with a partial intralamellar placement have a tendency to evert the intralamellar portion of the wound (Fig. 5.91a, b). This is avoided by a total intralamellar suture placement (Fig. 5.91c).[38] When closing the *side limbs*, it is useful to place the sutures obliquely to direct additional traction toward the apex (Fig. 5.90b).

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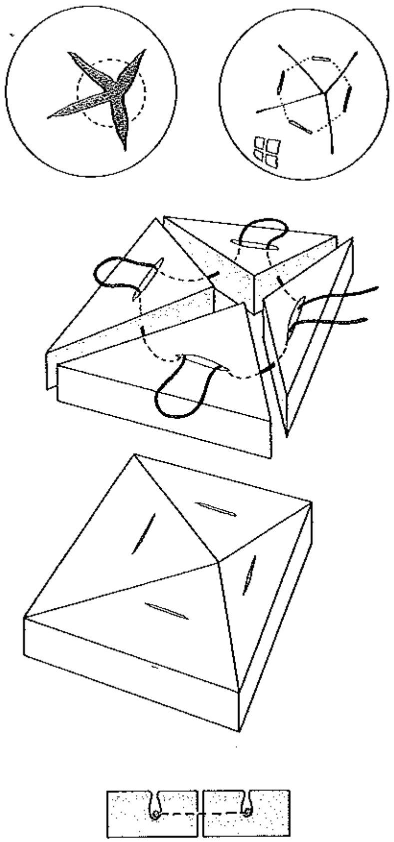
[35] This occurs when the angulation of the cutting instrument is varied during the corneal section. For example, segment A in Fig. 5.87 was made with the blade held upright, resulting in a narrow valve. The section was completed with scissors held less upright in segment B (moderately wide valve) and at a very low angle in segment C (very wide valve).

[36] This type of wound is made by flat, irregular missiles such as flying glass or a bursting shell.

[37] This type of wound is produced by objects with multiple edges, such as fragments of thick glass.

[38] *Note*: The intralamellar threads have a greater tendency to cut through the tissue than "normal" threads placed perpendicular to the surface because they are not anchored by the rigid Bowman's membrane. These sutures must be placed an adequate distance from the apex, therefore.

Fig. 5.92. Closure of a jagged wound with an intralamellar pursestring suture. A partial-thickness corneal incision is made with an ultrasharp blade next to each flap, analogous to Fig. 5.91c. A pursestring suture is passed through these grooves and is tightened to approximate the apices of the flaps



In wounds involving a **tissue defect**,[39] closure often cannot be effected simply by reapproximating the wound margins with sutures. If the defect is small, *relaxing incisions* may mobilize the tissue sufficiently to allow watertight closure (Fig. 5.93). Larger defects require reconstruction with corneal or scleral grafts.[40]

The suturing of **corneal disks** basically follows the hinge rule. The *first hinge* is formed as soon as the disk is fixed with two sutures. Additional sutures serve to subdivide the wound into watertight segments. The number of segments is dictated by the *hinge rule* for flaps that open *inward* (see Fig. 5.32).[41] Thus, a disk with a small diameter requires more sutures per unit wound length (i.e., more closely spaced sutures) than a large disk. Also, more sutures are needed when placed superficially than when placed deeply (see Fig. 5.34).

Circular wounds are especially challenging in terms of achieving uniform tension along the wound line. Even a single suture placed too tightly can cause gaping along the whole circumference of the wound (Fig. 5.94). Continuous sutures distribute tension uniformly and in fact are ideal for suturing corneal disks, because the circular shape eliminates the inherent disadvantages of the running suture (Fig. 5.95).

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[39] Such as an inveterated wound containing incarcerated foreign material (foreign body, iris prolapse, lens capsule, etc.). If a long interval passes from trauma to treatment, the wound margins will stiffen in a gaping position as a result of tissue organization, and removal of the incarcerated material will leave a defect. Similar problems can arise when an attempt is made to close an antiglaucomatous fistula secondarily.

[40] In some cases coverage of the wound area with a conjunctival flap may be necessary to improve watertightness.

[41] The standard rules of wound closure apply only if specific conditions are met: Closure by the valve mechanism is possible only if the wound surfaces are smooth and congruent; irregular wound surfaces require compression sutures to provide a contact area adequate for closure. The hinge rule applies only if there is sufficient tissue tension. In trephining, then, the primary task of sutures is to make the disk tense, the number of sutures depending on the inherent elasticity of the tissue. Once sufficient tension is achieved, the definitive number of sutures depends on the hinge rule.

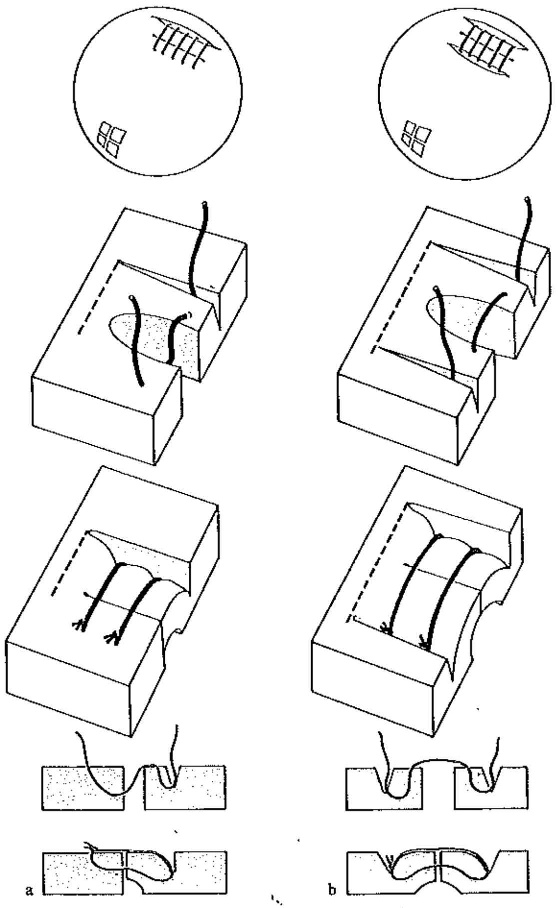

Fig. 5.93. Repair of small tissue defects. Use of relaxing incisions to obtain scleral or corneal sliding flaps. (*Note*: Corneal flaps must be de-epithelialized before use.)

a A partial-thickness incision made some distance from the wound margin mobilizes the superficial tissue layer, allowing it to be swung into the defect. *Note!* The relaxing incision must be longer than the defect to be repaired!

b Relaxing incisions may be used on both sides of the defect

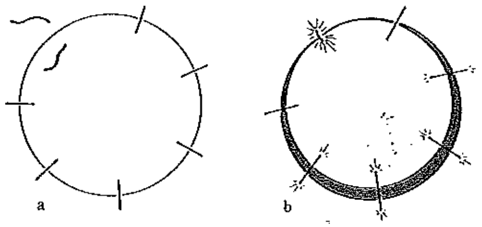

Fig. 5.94. Simple interrupted sutures in corneal disks. Tightening of sutures placed perpendicular to the wound margin.

a If suture tension is uniform, the wound edges are pressed together uniformly about their circumference.

b If even one suture is overtightened, the entire wound gapes

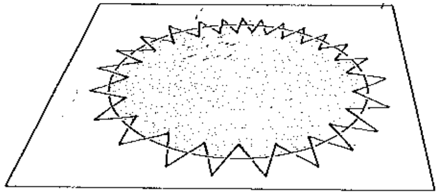

Fig. 5.95. Continuous sutures in corneal disks. In circular wounds the side effects of continuous sutures play a minor role. The tendency of continuous sutures to move onto one plane when tightened (see Fig. 2.103a) may not flatten the dome, because a circular wound is already on one plane. The lateral shifting tendency on suture tightening is of no consequence in a circular wound (see Fig. 2.111)

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6 Operations on the Ciliary Body

The ciliary body is attached to the ocular wall at the *scleral spur*. This band of attachment forms a barrier between the anterior chamber and the sclerochoroidal interspace, and any changes in that barrier will affect the intraocular pressure. Operations on the ciliary body consist either in *separating* the ciliary body from its attachment (*cyclodialysis*) or *reattaching* the ciliary body to the scleral spur (*cyclopexy*).

6.1 Cyclodialysis

Detachment of the ciliary body is accomplished with a *blunt spatula* whose shape conforms to the curved inner surface of the sclera. The spatula is introduced through a scleral incision into the sclerociliary space and passed along the inner scleral surface toward the anterior chamber. Injury to the vulnerable, vascular uvea is avoided by *pulling the sclera away from the uvea* with the spatula rather than pushing the uvea from the sclera.[1] All the manipulations in cyclodialysis, then, are accomplished essentially by outward traction. This produces a visible external bulge in the sclera which aids the operator in recognizing the position of the spatula.

Patency of the cyclodialysis can be maintained by the injection of *viscoelastic material*. However, the high resistance at the scleral spur may cause the material to flow back beneath the choroid during the injection. Therefore, following the rule for the application of viscoelastic materials (see Fig. 2.20) the resistance at the scleral spur is overcome by first probing with the rigid cannula before injecting the material (Fig. 6.1).

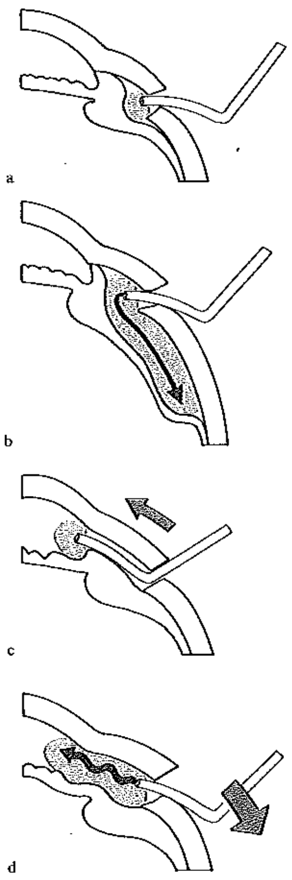

Fig. 6.1. Injection of viscoelastic material for cyclodialysis

a, b Technique leading to inadvertent filling of the sclerochoroidal space.
c, d Correct technique for maintaining separation of the ciliary body.

a If the injection is started immediately after inserting the cannula into the sclerociliary space, the resistance at the scleral spur will deflect the flow of viscoelastic material.

b The material is diverted backward into the space between the sclera and choroid.

c This is avoided by first passing the cyclodialysis cannula into the anterior chamber to dissect the ciliary body from the scleral spur.

d The viscoelastic material is injected on withdrawal of the cannula. It expands and maintains the communication formed between the anterior chamber and sclerociliary space

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[1] Avoid the horizontal meridian with the long posterior ciliary arteries!

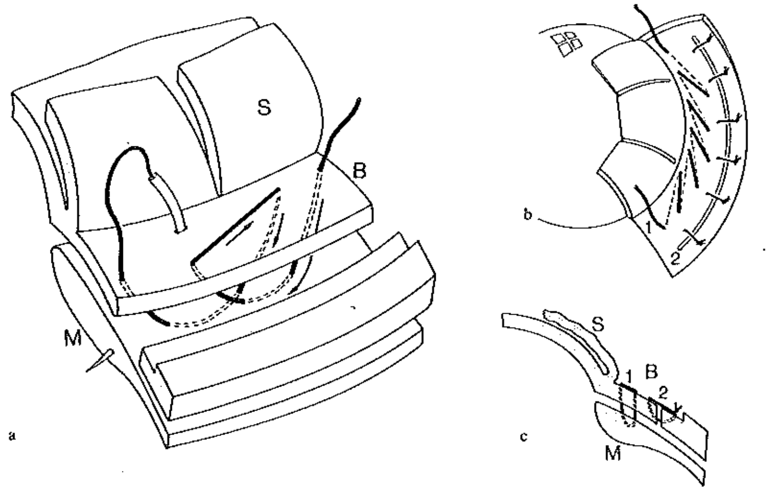

Fig. 6.2. **Cyclopexy with continuous overlapping sutures.** **a** Perspective view of the suture in a scleral "step" incision. **b** Overhead view, **c** cross section. A lamellar dissection of the sclera has been performed along the limbus, and the scleral flap (*S*) has been divided into several segments (see Fig. 1.54) and reflected. The thinned scleral bed (*B*) is incised to expose the detached ciliary muscle (*M*). A continuous suture technique is used in which the needle is reintroduced behind the previous point of emergence, so that the overlying segments run counter to the direction of the overall suture line. *1*, continous suture for cyclopexy; *2*, single loops for closure of scleral bed

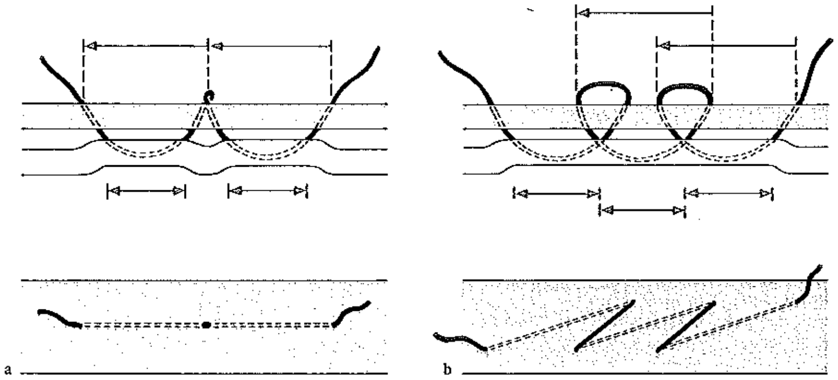

Fig. 6.3. **The problem of suturing layers together with a circular needle.** *Top*: Longitudinal section through the two layers. *Bottom*: Overhead view of the superficial layer.
Arrows top: Tissue of superficial layer encompassed by the suture.
Arrows bottom: Encompassed tissue of the deep layer.

a Because of the curved shape of the needle, a suture that is continuous in the superficial layer may leave discontinuities in the deep layer. The magnitude of this discrepancy for a given needle curvature depends on the thickness of the upper layer.

b If the suture that is to tack the lower layer to the upper layer without gaps, the needle must be reintroduced behind the previous point of emergence in each pass so that an oblique, overlapping suture pattern is obtained (analogous to the shingles on a roof)

6.2 Cyclopexy

A disinserted ciliary body can be surgically reattached to reestablish an effective barrier against fluid drainage from the anterior chamber.[2] The suture used for the cyclopexy must fix the ciliary body to the sclera without leaks so that it effectively prevents fluid seepage between the layers (Fig. 6.2). Such leaks may go undetected when the suture track is observed on the scleral surface, because a curved suture needle passed through a tissue layer encompasses a much larger area at the surface than below the layer (Fig. 6.3a). Thus, a suturing technique for uninterrupted fixation requires that the needle be reinserted *behind* its site of emergence when each stitch is made, resulting in an overlapping suture pattern (Fig. 6.3b). Because the discrepancy between the distances spanned by the suture on the upper and lower scleral surfaces depends on the thickness of the pierced scleral tissue, placement of the suture is facilitated by preliminary thinning of the sclera. This also lowers the tissue resistance, enabling the use of fine needles that will cause minimum trauma to the delicate tissue of the ciliary body.

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[2] E.g., to correct the hypotensive effect of an overfunctioning surgical cyclodialysis or to repair a traumatically disinserted ciliary body.

7 Operations on the Iris

Healthy iris tissue tends to return spontaneously to its original shape when displaced or deformed owing to its elastic resiliency and the action of the pupillomimetic muscles. However, these forces are weak and cannot overcome even a small frictional resistance. If the anterior chamber has drained or if the iris comes into contact with *air bubbles* or *viscoelastic material*, the iris tissue loses its inherent mobility and will regain it only when reimmersed in *watery fluid*.[1]

7.1 Iris Displacement and Reposition

Owing to its very high mobility, the iris can be partially exteriorized from the anterior chamber and operated on outside the globe. We can distinguish, then, between *intrabulbar* and *extrabulbar* iris operations (Fig. 7.1).

The iris can be exteriorized by means of *traction* (with forceps) or *pressure* (expression). Expression is accomplished by first apposing the iris to the incision, effectively making it part of the chamber wall, and then raising the intraocular pressure until the iris prolapses from the eye (Fig. 7.3).[2] Because the tissue in this prolapse is distended as well as displaced, the actual amount of iris extruded from the eye cannot be determined from the size of the prolapsed bleb. This amount can be estimated, however, by evaluating the *undistended* iris tissue remaining in the anterior chamber (Fig. 7.2).

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[1] Pupillomimetic agents per se are ineffective in these situations and therefore should be combined with the injection of watery fluid.

[2] Iris prolapsing spontaneously through the incision when the anterior chamber is entered signifies an elevated intraocular pressure that must be quickly brought under control (main danger: Expulsive hemorrhage!).

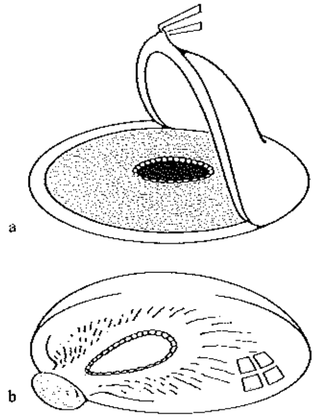


Fig. 7.1. **Approaches for iris operations**

a In the intrabulbar approach, the iris remains in its natural position while surgical instruments are passed into the anterior chamber.

b In the extrabulbar approach, the iris is brought out of the anterior chamber and operated on outside the eye

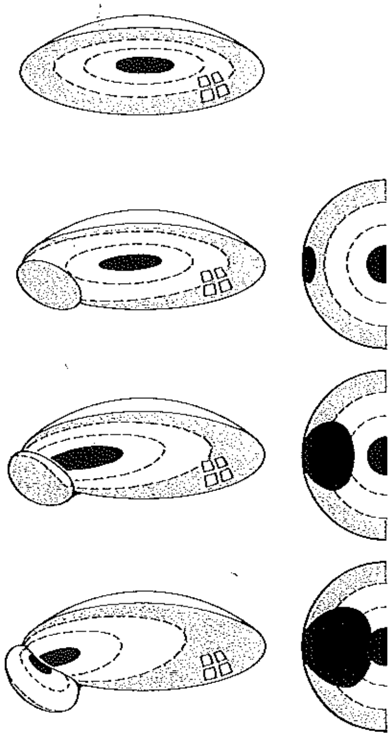
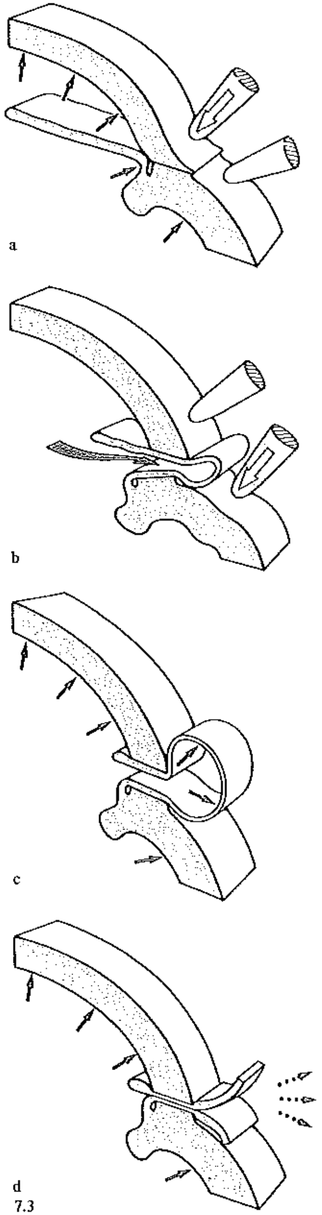


Fig. 7.2. **Visual evaluation of prolapsed iris tissue.** The size of the prolapse is a poor indicator of the quantity of exteriorized tissue. A better indicator is the position of the pupil, which shows how much iris remains in the anterior chamber. For clarity, the drawing shows the iris divided into concentric zones colored different shades of gray. *Left*: All the prolapses appear to be of nearly equal size, but contain different amounts of tissue. *Right*: The true extents of the prolapsed iris are shown in *black*. They indicate the size of the iridectomy that would result if the prolapsed tissue were sectioned flush with the eye surface



7.3. **Expression of the iris**

a Two blunt expressors (e.g., spatulas) are applied to the wound margins. The pressure on the upper instrument seals off the valvular wound and initially raises the intraocular pressure.

b Next the lower instrument is slightly depressed to open the wound and allow extrusion of the iris by the intraocular pressure.

c While lining the wound, the iris becomes part of the ocular wall. A further rise of intraocular pressure will stretch the iris more than the cornea, causing it to bulge outward. The prolapse has the same pressure as the anterior chamber.

d Incising the prolapse destroys its status as a pressure chamber. Once the prolapse has collapsed, additional iris will not be extruded by a further rise in intraocular pressure. Instead, the pressure rise reactivates the valvular mechanism of the wound, and the iris tissue is incarcerated

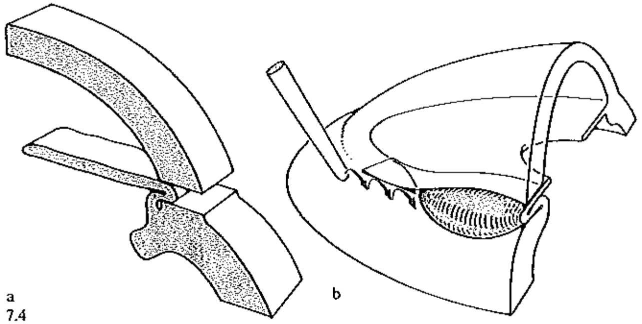


Fig. 7.4. **Repositioning the iris by tapping the wound**

a Incarceration of iris in the wound.

b Reposition is effected by tapping along the lower wound margin to momentarily reopen the wound and allow the prolapsed iris to retract into place. This is started well back from the outwardly visible prolapse, because the incarceration is considerably larger internally (*light gray*) than its external portion (*dark gray*) would suggest

The first step in *repositioning* the prolapsed iris is to eliminate the factor sustaining the prolapse – the raised intraocular pressure. This pressure is lowered by the removal of aqueous, either by allowing the fluid to drain adjacent to the prolapse (by briefly opening the incision) or by incision of the prolapse itself (Fig. 7.3d). The repositioning maneuver is then completed by aiding spontaneous retraction of the iris or by using an iris repositor.

To fully utilize the **retractile tendency** of the iris, it is necessary to decrease frictional resistance. Friction at the *incision* is eliminated by separating the lips of the incision, taking care in critical situations to hold the wound open as briefly as possible (Fig. 7.4).[3] Friction inside the *anterior chamber* is reduced by the injection of watery fluid, to which a miotic (e.g., 0.1%–0.5% acetylcholine) may be added if necessary to stimulate the repositioning action of the iris musculature (Fig. 7.5).

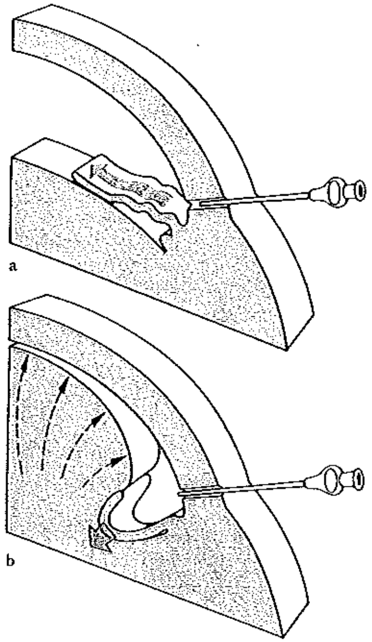


Fig. 7.5. **Repositioning the iris by refilling the anterior chamber**

a The gentle injection of a fluid stream (which may contain a miotic) restores iris mobility and aids spontaneous reposition.

b If the iris is driven downward by a direct fluid jet, the compensatory upwelling of vitreous forms a "mushroom" that hinders pupillary contraction (this is prevented by injecting through a "watertight" orifice thus restoring the pressure chamber, see Fig. 2.25)

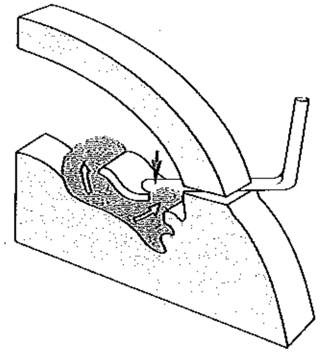


Fig. 7.6. **Repositioning the iris with a spatula** (for the case where there is viscoelastic material behind the iris). The viscoelastic material is not removed from behind the iris by stroking the spatula just in a horizontal direction. The spatula must also press the iris downward (*red arrow*) to extrude the viscoelastic material through the pupil (and through any iridectomy) (*black arrows*). *Note:* The spatula should be moved slowly and held in the depressed position for sufficient time to allow the viscous fluid to flow away

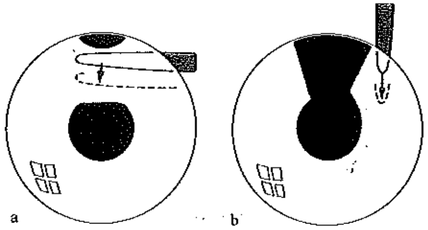


Fig. 7.7. **Repositioning the iris by stroking the stroma.** Spatula movements that go beyond the stroma into the pupil or iridectomy do not improve the effect and actually endanger structures deep to those openings.

a Following peripheral iridectomy, the spatula is inserted beneath the iridectomy from the side and stroked toward the pupil with its long (blunt) side leading.

b Following a sector iridectomy, the spatula may be stroked parallel to the iridectomy and pupil, but not toward them

Iris reposition can also be effected directly by applying **spatulas** (repositors) to the trabeculae. In a *watery* milieu the spatula can be stroked horizontally in the natural direction of the iris trabeculae. But if *viscoelastic material* has been placed behind the iris, the spatula also must be pressed downward to indent the viscous mass (Fig. 7.6). Care is taken to *direct* the repositor in a way that avoids vectors toward the pupil or iridectomy; this ensures that any excessive motion of the instrument will not harm structures behind the iris plane (Fig. 7.7).

The success of the repositioning maneuver is judged from the position of the trabeculae, the collar-

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[3] If the vitreous pressure has not been adequately lowered, keeping the incision open too long will only aggravate the iris prolapse and may allow the undesired prolapse of other intraocular tissues.

Fig. 7.8. Diagnosis of iris incarceration

a Discrete incarceration in distensible tissue. The pupil retains a normal shape and position, because the tissue between the pupil margin and incarceration site is adequately distended. This distention, signifying incarceration, is evidenced only by a displacement of the collarette.

b Discrete incarceration in poorly distensible tissue. The pupil is distorted into an ellipse whose long axis points toward the incarceration site. Note that here the collarette is uniformly distant from the pupil margin

7.8

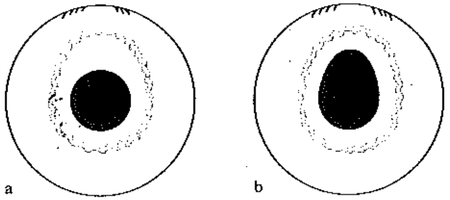


Fig. 7.9. Iris incarceration in a peripheral iridectomy

a The criterion for successful iris reposition after peripheral iridectomy is a pupil flattened on the side of the iridectomy, since division of the iris root causes the sphincter force to predominate at that location.

b A round pupil following peripheral iridectomy may signifie an incarceration of iris tissue (check the position of the collarette! See Fig. 7.8a)

7.9

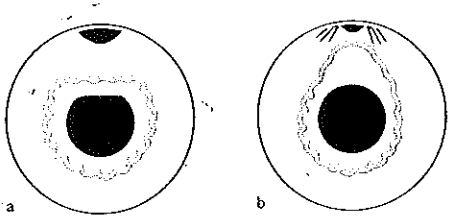


Fig. 7.10. Incarceration in a sector iridectomy

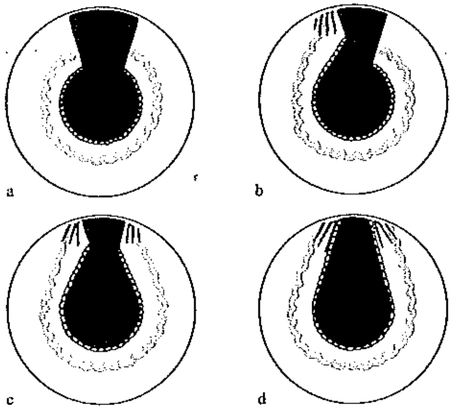
a The criteria for successful iris reposition: The pupil margin and the collarette are everywhere equidistant from the root, the sides of the iridectomy are of equal length, and its corners are well formed.

b Partial unilateral incarceration: The pupil margin is displaced upward, and one corner is blunted.

c Partial bilateral incarceration.

d Total bilateral incarceration. The corners of the iridectomy are ill-defined, and the pupil margins extend toward the wound

7.10



ette, and the *shape of the pupil* (Figs. 7.8–7.10).

Failure of all these maneuvers implies the presence of *other obstructions* such as incarcerated lens capsule or vitreous. Clearing these obstructions exceeds the bounds of simple iris reposition and necessitates more extensive measures geared toward the properties of the tissues involved.

7.2 Grasping and Cutting

Because the iris tissue is so mobile, its sectility is low. On the one hand this is helpful in preventing iris injury, but on the other it complicates the conduct of precise manipulations. Due to the *forward shifting tendency* of the iris (see Fig. 2.62), incisions are shorter than the distance actually traveled by the cutting edge. Thus, if the cut is to be made with a single snip of the scissors, the blades must be considerably longer than the proposed incision.

The *lateral shifting tendency* causes tissue to shift toward sites of anatomic or instrument fixation (see Fig. 2.63). In the *ungrasped* iris the tissue shifts toward the iris root, so that the resulting incision deviates toward the pupil (Fig. 7.11a). Grasping the iris with *forceps* creates new fixation sites (Fig. 7.11b), and the shift tendencies become more complex: The tissue between the iris root and forceps behaves like tissue with bilateral fixation, so the "rule of retraction" applies (see Fig. 2.64). There is only unilateral fixation between the forceps and pupil. This produces a lateral shifting tendency whose extent depends on the countertraction of the iris sphincter.

Fig. 7.11. Shifting tendencies caused by unilateral fixation

a Tissue ahead of the cutting edge tends to shift toward the periphery (*thick arrows*), so that the resulting cut deviates progressively toward the pupil. This tendency can be partially offset by the pull of the iris sphincter (*thin arrows*). As a result, there is a marked tendency toward peripheral tissue shifting in mydriasis, but in miosis this tendency can be neutralized by sphincter traction.

b Grasping the iris with a fixation forceps creates two zones in which different tensions prevail. From the iris root to the forceps (peripheral zone *B*), the iris behaves as if it were fixed bilaterally, but from the forceps to the pupil margin (pupillary zone *P*) it behaves as if fixed unilaterally (i.e., by the fixation forceps alone)

7.11

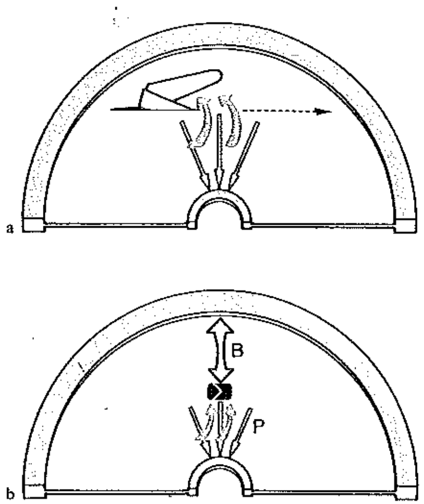
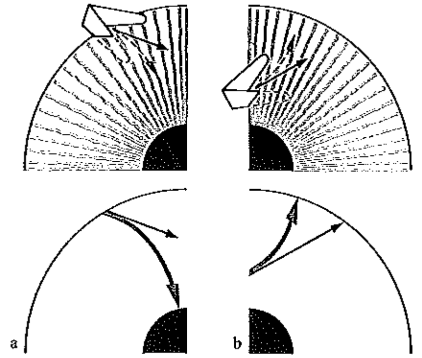


Fig. 7.12. Lamellar deflection in the Iris. The cut tends to deviate onto a path parallel to the iris trabeculae.

a Cuts angled away from the iris root tend to deviate toward the pupil (*red arrow*). This leaves more tissue in the area between the iris root and the incision than planned.

b Cuts angled toward the periphery are deflected onto a path perpendicular to the iris root. The area between the iris root and the incision (*red arrow*) is smaller than that corresponding to the guidance direction (*black arrow*). The discrepancy between the intended cut and the resulting cut is shown in pink (*below*)

7.12



Lamellar deflection is a less important phenomenon in the iris, but it can affect an incision that is carried obliquely across the trabeculae (Fig. 7.12). The extent of the deflection depends on the difference between the resistances of the trabeculae and the interstitial tissue.[4]

Pathologic tissue changes[5] can radically alter the tactics of iris operations. The altered iris tissue becomes inelastic and immobile; thus it becomes more sectile and tears in response to the slightest insult. The primary task of the surgeon in this situation is to *restore iris mobility*. Pathologic fixation to surrounding tissue (synechiae) must be divided, and rigid tissue must be mobilized by relaxing incisions.

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[4] Thus, lamellar deflection is most conspicuous in the pale iris and less so in the heavily pigmented iris, which has a more homogeneous structure.

[5] E.g., scarring after inflammations, atrophy following acute glaucoma or previous laser treatments, pronounced senile degeneration, etc.

7.3 Iridectomies

It is difficult to predict the exact size of an iridectomy because of the shifting tendencies of the tissue, which change constantly during manipulations. When dealing with a specific clinical problem, therefore, the surgeon must decide which criteria are the most important (e.g., securing a basal position of the iridectomy, Fig. 7.13) and where compromises may be tolerated (e.g., the shape and size of a peripheral iridectomy).

The basic technique for iridectomy is to excise the tissue at the apex of the pyramid formed when the tissue is tented with a forceps. The portion of the pyramid lying above the guidance path of the scissors is excised, and the underlying portion retracts into the anterior chamber. But the shape of the iridectomy cannot simply be estimated from the geometry of the pyramid and the plane of the scissors, because the different faces of the pyramid are under different degrees of tension (Fig. 7.16). Thus, excisions in pyramids of identical geometric configuration can yield strikingly different results.

Controlling the shape and position of the iridectomy is basically a matter of properly coordinating the *fixed* and the *variable* quantities that are associated with the cutting and grasping of iris tissue.

A major *fixed, predetermined quantity* in **cutting** is the starting point of the iridectomy, i.e., the site where the scissors are applied. Also predetermined is the longitudinal axis of the excised oval, which follows the direction of motion of the cutting point, i.e., the direction of the scissor blades (Figs. 7.14, 7.15). The width of the iridectomy is *variable*, however, for it depends on the shifting tendency of the tissue. The length of the iridectomy is also variable for the same reason (except when the cut is directed toward the iris root, see Fig. 7.15).

Another factor affecting the size of an iridectomy is the *bleb* of iris tissue that forms above the scissor blades as closure of the blades is initiated. As the pressure inside the bleb rises, it can create an additional force that shifts the tissue ahead of the scissor blades. When the blades are closed slowly, surrounding iris tissue tends to be drawn into the bleb, which becomes progressively larger.[6] Once incised, however, the bleb collapses, and part of the tissue previously drawn into the bleb retracts to its former position.[7] Thus, there is a "*bleb phase*" of the iridectomy in which the excision tends to be larger than planned and a "*collapse phase*" in which the excision becomes smaller. The precision of the cut can be improved by closing the scissors rapidly and allowing no time for shifting to occur.

On **grasping**, the site of application of the forceps determines several *fixed quantities*: the minimum

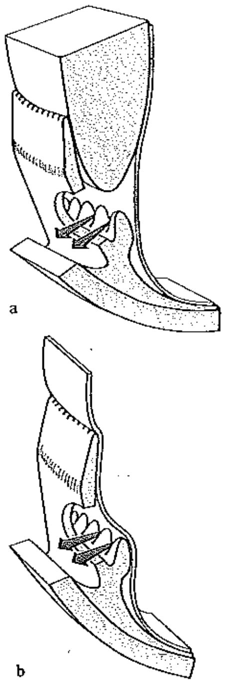

Fig. 7.13. Size and placement of an iridectomy to restore aqueous circulation in case of pupillary block. Adhesion of the margins with surrounding structures is avoided by placing the iridectomy so that it cannot come in contact with neighboring tissues. Peripheral placement of the iridectomy will ensure adequate clearance of the iris from the lens capsule and anterior hyaloid in both the phakic (a) and aphakic eye (b). Contact is unlikely even with a lax and bulging anterior hyaloid, because the ciliary processes act like a rake to hold the membrane back. The size of the iridectomy is less critical than its placement. The only caveat is that the opening should not project far enough into the optical axis to cause visual disturbance (e.g., diplopia)

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[6] This tendency is strongest when the scissor blades are long and the interblade angle is small during cutting (e.g., de Wecker's scissors).

[7] This may happen with a short-bladed scissors that cannot transect the whole iris pyramid at once (e.g., Vannas scissors).

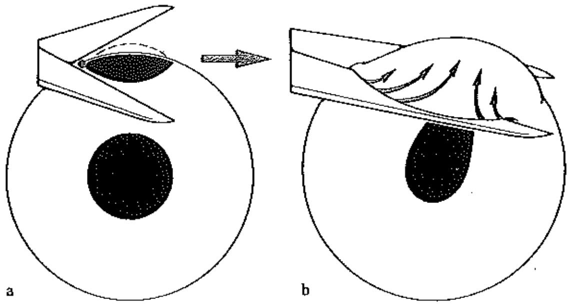


Fig. 7.14. Directing the scissors parallel to the iris root

a Directing the scissors parallel to the iris root produces a broad iridectomy with a transverse oval shape. The site where the cutting point is applied (*red*) defines the position of one lateral edge of the iridectomy, but the maximum pupillary extent and end point cannot be predicted.

b The tissue is shifted peripherally by the advancing cutting point. The resulting iridectomy extends farther toward the pupil than the blade position would indicate. There is a risk of sector (pupil-to-root) iridectomy

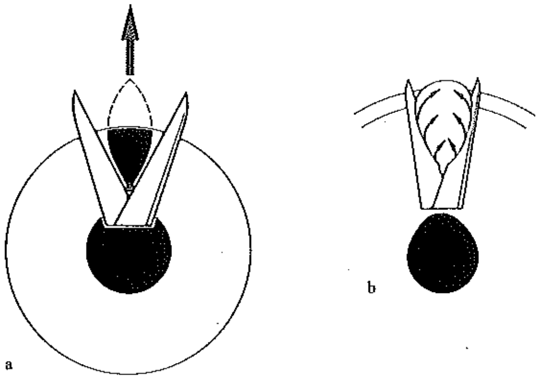


Fig. 7.15. Directing the scissors toward the iris root

a Cutting toward the iris root produces a narrow iridectomy with a radially oriented longitudinal axis. The maximum pupillary extent is determined by the site where the cutting point is applied (*red*).

b The lateral extent depends on the mobility of the tissue gathered toward the cutting point from both sides. This mobility is constrained by the lamellar structure of the trabeculae (see Fig. 7.12a) and the peripheral fixation

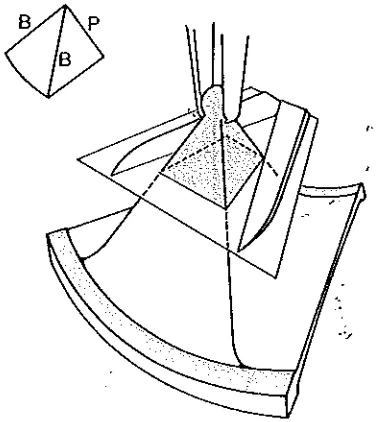
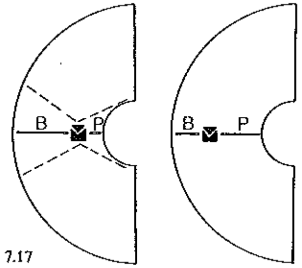


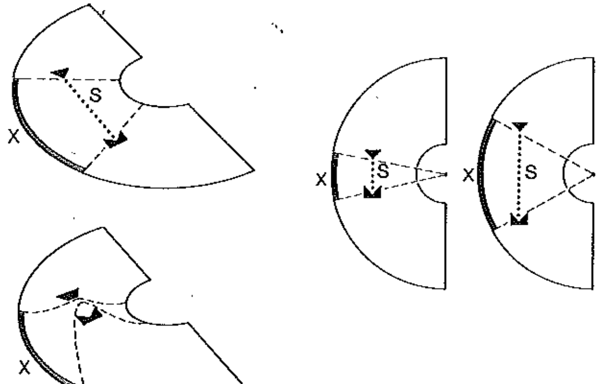
Fig. 7.16. Forming and sectioning the "iris pyramid." Traction on the grasping forceps raises the iris into the shape of a pyramid. All tissue located above the guidance path of the scissor blades (*red*) is excised. If the pyramid were composed of firm, noncompliant material, either raising the forceps or lowering the plane of the scissor guidance path would yield the same result. But the iris is compliant, resilient, and is fixed unilaterally at its root; therefore each of these actions produces a different result.
B: Peripheral (basal) portion of pyramid
P: Pupillary portion

distance of the excision from the iris root (Fig. 7.17), the minimum peripheral width of an iridectomy directed toward the iris root (Fig. 7.18), and the minimum size of the iridectomy (Fig. 7.19). *Variables* in the procedure relate to the force and direction of the traction that is applied. Changing the *strength of the traction* alters the tension on the *basal side* of the pyramid but does not affect the amount of tissue there; meanwhile the tension on the *pupil side* remains low, but the amount of tissue in that area is affected. Changing the *direction of traction* draws different portions of the iris across the plane of the scissors and incorporates them into the excision. Thus, traction toward the pupil draws more peripheral tissue into the excision, whereas centrifugal traction incorporates more of the central portion (Figs. 7.20, 7.21). The same effects can be achieved without moving the forceps simply by *changing the inclination of the scissors* (Fig. 7.22).



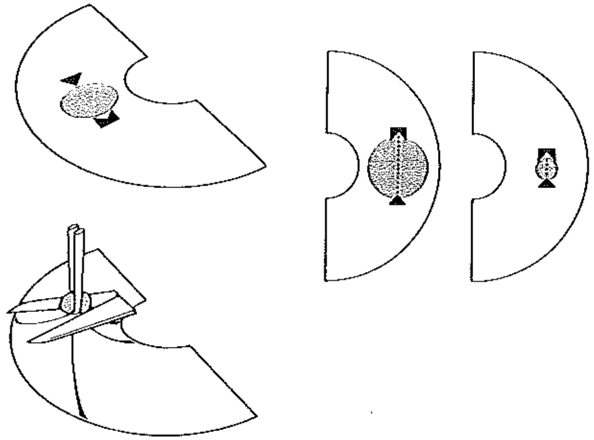
7.17

Fig. 7.17. Fixed quantities determined by application of the forceps. The forceps placement determines the *distance from the pyramid apex to the iris root* (*B*) and to the pupil (*P*). Because the application site is always included in the excision, it determines the minimum distance of the excision from the anatomic boundaries of the iris



7.18

Fig. 7.18. Fixed quantities determined by application of the forceps: Peripheral width of the iridectomy. At a given distance from the iris root, the separation of the forceps blades (*S*) determines the peripheral width (*X*) of the iris "pyramid" and thus the maximum peripheral width of the iridectomy (*left*) that can be achieved by sectioning the pyramid with one snip of the scissors. *Right*: Examples of basal widths for different blade separations



7.19

Fig. 7.19. Fixed quantities determined by application of the forceps: Minimum size of the iridectomy. *Left*: The blade separation determines the minimum size of the iridectomy (*top*), which can be no smaller than the area grasped between the blades (*bottom*). *Right*: Examples of minimum iridectomy size for various blade separations

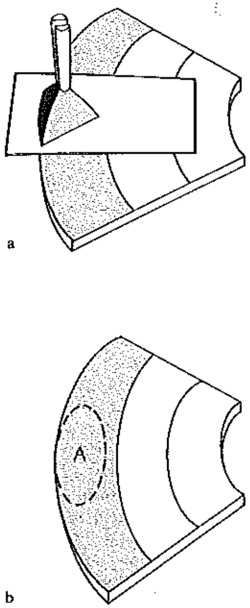
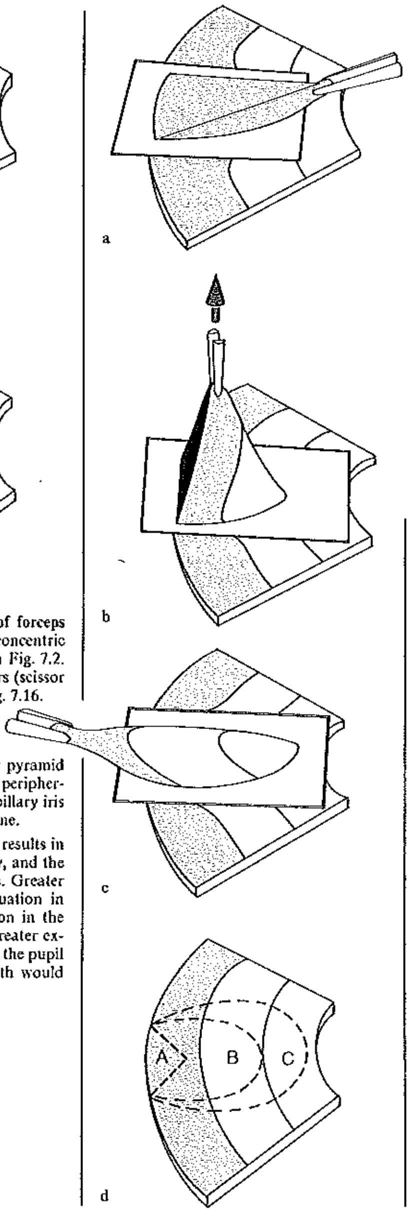


Fig. 7.20. Effect of the degree of forceps traction on the iridectomy. The concentric gray zones follow the pattern in Fig. 7.2. The guidance path of the scissors (scissor plane) is outlined in *red* as in Fig. 7.16.

a Mild traction produces a low pyramid which places little tension on the peripheral iris and draws little of the pupillary iris (*dark gray*) across the scissor plane.

b Excised area. The low tension results in a strong lateral shifting tendency, and the iridectomy has rounded margins. Greater traction would produce the situation in Fig. 7.21 b, with increased tension in the peripheral iris (*dark gray*) and greater extension of the iridectomy toward the pupil (*light gray*). The peripheral width would remain unchanged



◄ **Fig. 7.21. Effect of the direction of forceps traction on the iridectomy.** Changing the direction of the traction without changing its magnitude does not affect the peripheral iris tension but does affect the amount of tissue drawn from the pupillary portion above the plane of the excision.

a Traction toward the pupil yields the smallest iridectomy (includes only the *dark gray* zone). Because the peripheral iris is very tense (in contrast to Fig. 7.20a), the iridectomy is narrower and has straight margins (see **d**).

b Upward traction draws part of the central iris into the iridectomy (*light gray* zone).

c Traction toward the iris root draws more pupillary tissue above the scissor plane (*white* zone).

d Iridectomies *A*, *B* and *C* obtained in situations **a**, **b** and **c**

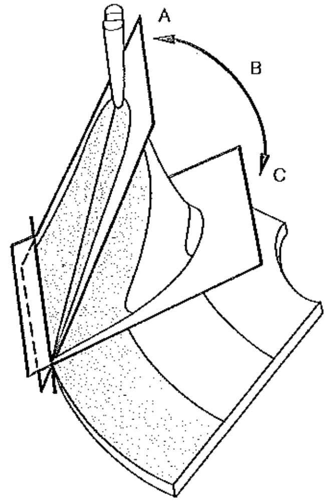


Fig. 7.22. Effect of the angle of scissor application on the iridectomy. By changing the inclination of the scissors while holding the forceps stationary, the surgeon can tailor the iridectomy just as he can by changing the direction of forceps traction while holding the scissors stationary. The iridectomies resulting from scissor positions *A* and *B* correspond to those in Fig. 7.21 d

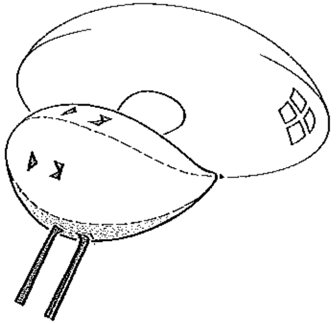


Fig. 7.23. **Extrabulbar iridectomy.** Because the tissue in the prolapse is stretched, it is difficult to estimate the true distance between the site of forceps application (*red*) and the iris root. An iridectomy of minimum size is obtained by grasping the prolapse as close as possible to the basal lip of the incision (*dark gray* zone). Grasping at sites higher on the bleb yields larger iridectomies. The maximum width of the iridectomy at the root is limited by the width of the incision

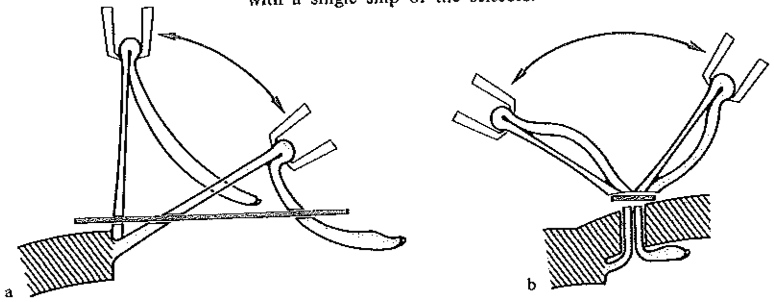


Fig. 7.24. **Effect of the direction of traction on intrabulbar and extrabulbar iridectomies**

a In an intrabulbar iridectomy, changing the direction of traction brings new tissue above the guidance plane of the scissors (*red*); this alters the shape of the iridectomy as in Fig. 7.21.

b In an extrabulbar iridectomy, changing the *direction* of traction does not affect iris lying above the guidance plane. Thus the shape of the iridectomy depends on the *degree* of traction rather than its direction

Performing an **extrabulbar** iridectomy changes the distribution of tension on the iris tissue and alters its topography. When the iris is **grasped** with a forceps, it is more difficult to estimate the distance between the site of forceps application and the anatomic boundaries of the iris (root, pupil margin) (Fig. 7.23). The maximum *peripheral width* of the extrabulbar iridectomy is no longer determined by the separation of the forceps blades (see Fig. 7.18) but depends chiefly on the width of the corneoscleral incision, for only tissue lying directly below the opening can be sectioned close to the root (tissue drawn into the prolapse from the side is not divided at the root). As in the intrabulbar procedure, the *amount of tissue* that is drawn *across* the scissor blades depends on the *degree* of traction. The *direction* of the traction is of lesser importance, because friction at the lips of the incision creates a new fixation zone that hinders tissue movement from the pupillary zone (Fig. 7.24).

The main difficulty in **cutting** is to get close to the iris root. If this is attempted by pressing the scissor blades firmly against the ocular surface, there is a danger of raising the intraocular pressure and enlarging the prolapsed bleb. If the planned *size of the iridectomy* just equals the quantity of prolapsed tissue, enlargement of the bleb can be prevented by cutting the iris quickly with a single snip of the scissors. Alternatively, if the iridectomy is to be *smaller* than the prolapsed tissue, the bleb is incised and allowed to collapse before the excision is performed.

Although many factors influence the excision of freely mobile iris, there are several **practical guidelines** for the technique of iridectomy: The best precision is achieved by cutting *toward the iris root.* The maximum pupillary extent of the iridectomy is then determined by the site of scissor application, and lateral shifting is reduced by the high tension in the peripheral part of the pyramid and by cutting parallel to the trabeculae (Fig. 7.15). If the cut is made *parallel to the root,* however, the shifting tendencies of the tissue will tend to make the iridectomy larger than planned. In this case the pupillary extent of the iridectomy is not limited by the site of scissor application, but depends chiefly on iris mobility. The tissue will tend to shift continuously from the lax pupillary part of the pyramid toward the forceps or the root, this tendency being reinforced by the cross-trabecular trajectory of the cut (Fig. 7.14). The result of this may be an unintended sector iridectomy if the cut crosses the pupil margin.

The following practical examples serve to illustrate how the above tendencies can be utilized to achieve specific goals:

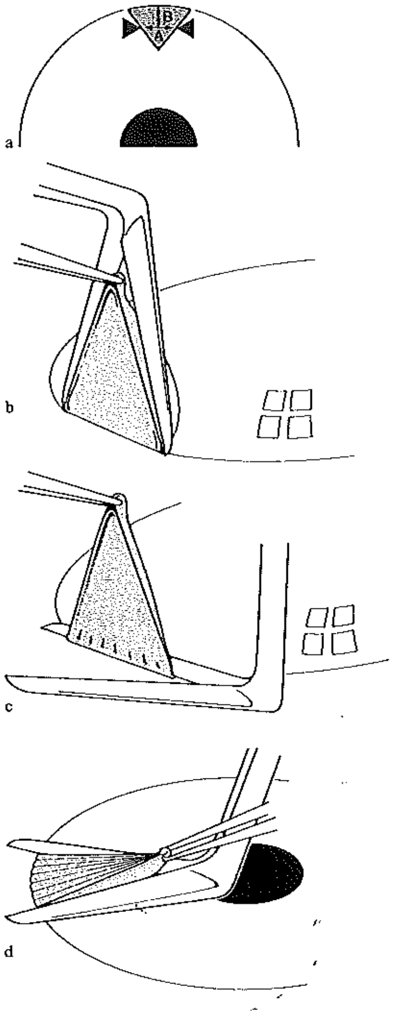


Fig. 7.25. **Objective: Peripheral iridectomy of minimal size.**
Grasping: Small blade separation (*A*) and short distance from iris root (*B*).
Traction: Firm in the direction of the cutting point.
Cutting: Position of guidance plane: In tense part of pyramid (i.e., just below forceps), close to traction fold, close to iris root. Guidance direction: Toward iris root.

a Diagram of planned shape of iridectomy.

b *Extrabulbar* iridectomy: Selection of tense portion by inclining the scissors.

c Excision of the incised triangle by cutting along the iris root.

d *Intrabulbar* iridectomy: Selection of tense portion by directing traction just above the scissor blades. Since the scissor blades are parallel to the iris plane, they may extend beyond the base. The excision is done with one snip of the scissors

A **peripheral iridectomy** of *minimum size* (Fig. 7.25) is obtained by cutting mostly in the tense portion of the pyramid. This places the iridectomy closer to the root by exploiting the retractile tendency of the iris tissue. Additionally, the cut is directed toward the root to define the maximum pupillary extent of the excision from the outset and reduce lateral shifting (see Fig. 7.15).

To obtain a peripheral iridectomy that is somewhat *larger than a given excised corneal opening,*[8] surrounding iris tissue must be drawn into the area between the scissor blades (Fig. 7.26). The blades are directed along the longitudinal axis of the corneal opening (Fig. 7.14).

A **sector iridectomy** made with a *single snip* of the scissors (Fig. 7.27) will always have rounded edges, because much of the excision is performed in lax tissue.[9] If the goal is a sector iridectomy with straight margins, the excision must be performed in *several steps* (Fig. 7.28).

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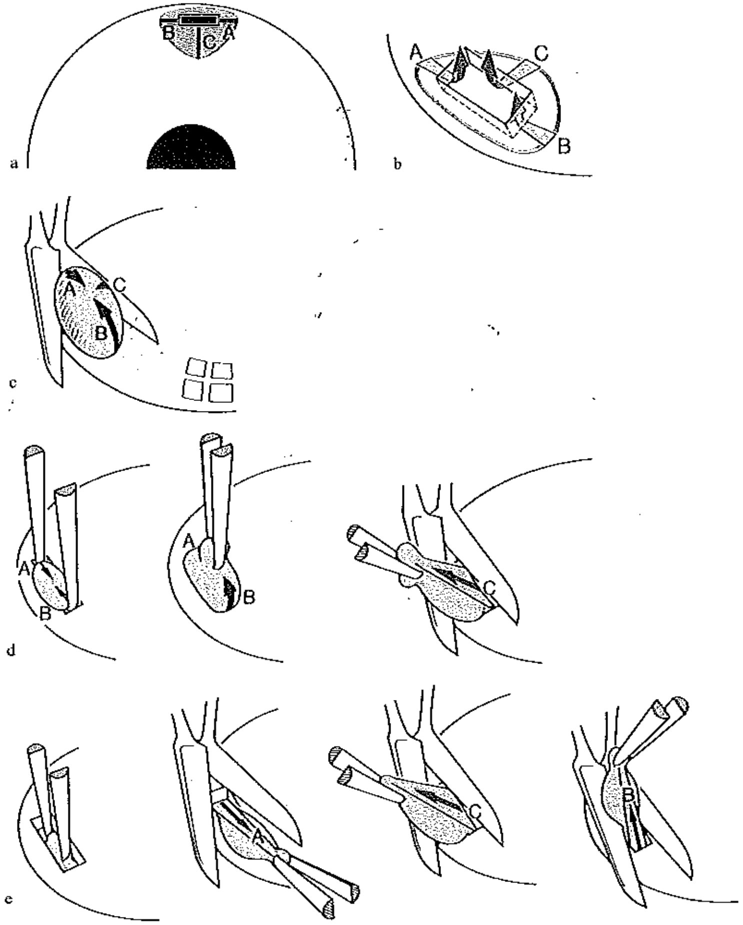
[8] E.g., in an antiglaucomatous fistula made with a trephine or scissors (trabeculectomy), the iridectomy may be made larger than the corneal opening to avoid synechiae with the wound margin.

[9] If the forceps is applied at the pupil margin to make the tissue tense, the resulting iridectomy will be triangular in shape, i.e., narrower peripherally than at the pupil.



7.26. Objective: Peripheral iridectomy larger than a given corneal opening

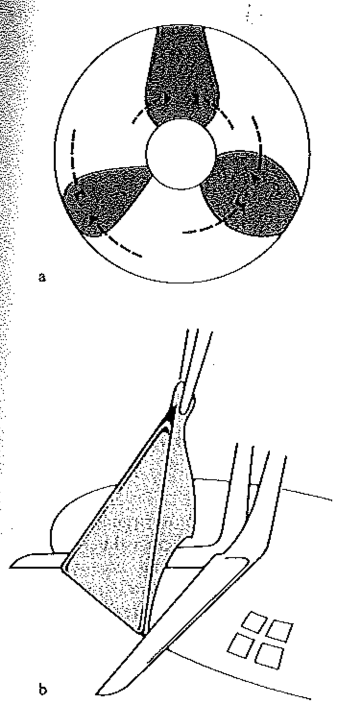
a Diagram of the planned shape of the iridectomy: The margins of the iridectomy are to lie at distance ABC from the margins of the corneal opening (black rectangle).

b *Task*: Iris tissue must be exteriorized from the areas corresponding to ABC.

c *First method*: Segments *ABC* are exteriorized by spontaneous prolapse. Control is difficult, and the effect is hard to judge due to stretching of the tissue (see Fig. 7.2).

d *Second method*: Segments *A* and *B* are exteriorized by closure of the forceps. If the forceps grasp the edges of a small spontaneous prolapse, segments A and B are both exteriorized by closure alone. Segment *C* is exteriorized by additional forceps traction toward the iris root.

e *Third method*: Segments *ABC* are exteriorized purely by forceps traction. If the iris is grasped with a small blade opening, forceps closure effects very little tissue displacement. Segments *A*, *B* and *C* are exteriorized by consecutive traction toward the scissors tip, iris root, and cutting point



7.27

Fig. 7.27. **Objective: Sector iridectomy with a single snip of the scissors**

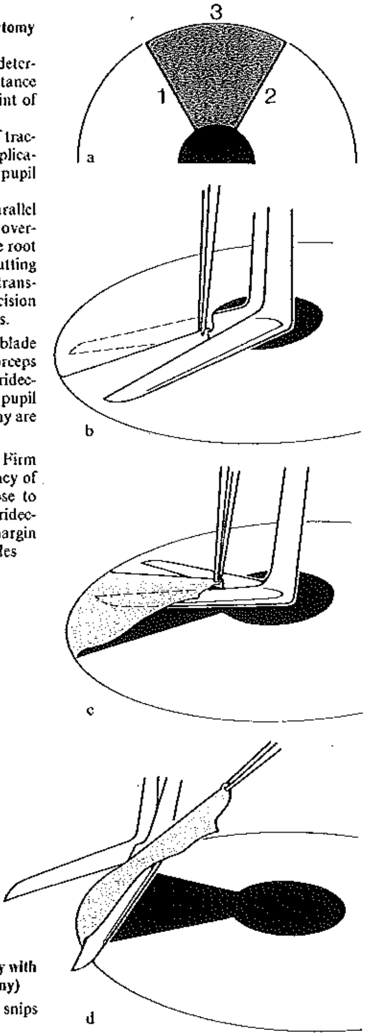
Grasping: Forceps blade separation determines the minimum width. The distance from the iris root determines the point of greatest width.

Traction: The direction and degree of traction depend on the site of forceps application. The traction serves to bring the pupil margin above the scissor blades.

Cutting: The blades are directed parallel to the iris plane so that the tips can overhang the iris root. Cutting toward the root produces upright ellipses as in **a**. Cutting parallel to the root would produce a transverse ellipse with a large stromal excision for similar pupillary and basal widths.

a Shape of iridectomy: For a given blade separation, the distance of the forceps from the iris root determines the iridectomy width at the root and at the pupil margin. The margins of the iridectomy are rounded.

b Criteria for controlling traction: Firm traction exploits the retractile tendency of the iris to place the iridectomy close to the iris root. In a single-snip sector iridectomy, it is essential that the pupil margin be drawn above the plane of the blades



7.28

Fig. 7.28. Objective: Sector iridectomy with straight margins ("keyhole" iridectomy)

a Diagram of iridectomy (with three snips of the scissors).

b Step 1: The pupil margin is grasped at one corner of the planned iridectomy. The cut is made along the traction fold (for minimum deviation).

c Step 2: A similar cut is made from the other corner.

d Step 3: Excision is completed along the iris root. Firm tension is applied to exploit the retractile tendency of the tissue

7.4 Synechiolysis

When a **solid spatula** is used for the blunt division of synechiae, it is directed in a way that maximizes tissue sectility (by increasing the tissue tension) and minimizes resistance (by applying the spatula at right angles to the adhesions) (Fig. 7.29).

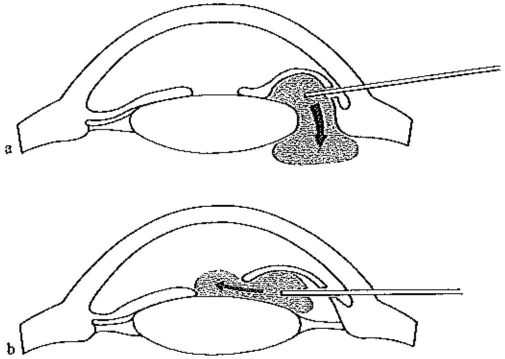


Fig. 7.30. **Separation of posterior synechiae with a viscoelastic spatula**

a If the resistance of the synechiae is higher than that of the zonule, the injected material may penetrate the zonule and cause an unintended zonulolysis.

b This is avoided by dividing the synechiae at one site with the tip of the injection cannula to allow surplus material to escape toward the pupil

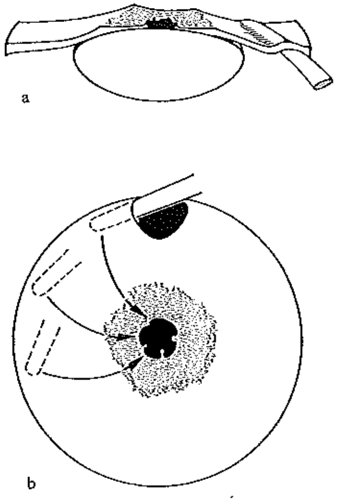
When **viscoelastic material** is applied as a "soft spatula," the material will flow along the path of least resistance. Thus, if the resistance at the pupil margin is high in the presence of posterior synechiae, the injected material may rupture the zonule and subluxate the lens rather than divide the synechiae (Fig. 7.30). This is avoided by preliminary synechiotomy with a *solid spatula* (this may be the injection cannula itself), creating a *path of low resistance* leading to the pupil. After preparation of this route of escape, synechiolysis with a soft spatula can begin.

Visual confirmation that the synechiolysis is proceeding well relies on an absence of concomitant motion in the rest of the iris stroma. Such motion is a warning sign that potentially damaging forces are being transferred to sites other than the synechiae. Thus, for example, if the synechial attachment is stronger than the anatomic attachment of the iris root,[10] any attempt to divide the synechiae would most likely cause an iridodialysis. Firm synechiae of this kind are better excised altogether and the resulting defect repaired by an iridoplastic procedure.

Fig. 7.29. **Separation of posterior synechiae**

a The spatula is inserted into an area presumed to contain no adhesions (i.e., the space peripheral to the lens margin). For visual control, the spatula position is indicated by a bulge in the iris (which can be accentuated by raising the spatula slightly without advancing it).

b The synechiae are cleared by sweeping the spatula in a centripetal direction, i.e., the direction in which the greatest tissue tension is produced (shortest path to fixation point at iris root) and resistance is minimal (smallest diameter of adhesion zone, *gray*)



7.5 Surgical Enlargement of the Pupil

The technique for enlarging the pupil depends on whether the pupil is incapable of dilating because of *nonresponse to mydriatics* or as a result of *pathologic structural changes* (Fig. 7.31).

If the *tissue structure is normal*, localized short-term dilatation can be effected with small hooks or contact retractors. **Iris hooks** pass around and engage the pupil margin. They are removed by pushing the hook slightly toward the center of the pupil (Fig. 7.32). **Contact retractors** retract the pupil margin by establishing direct contact with the lens surface and are easy to remove (Fig. 7.33). Soft *sponge swabs* effect temporary iris retraction by establishing direct contact with the lens (mechanical blocking action) and with the iris trabeculae (friction) (Fig. 7.34). Global mydriasis of longer duration can be produced by

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[10] Most adhesions with the lens capsule or corneal endothelium are easily divided with a blunt spatula, but adhesions with cortical remnants or corneal stroma may be too firm for this.

7.31

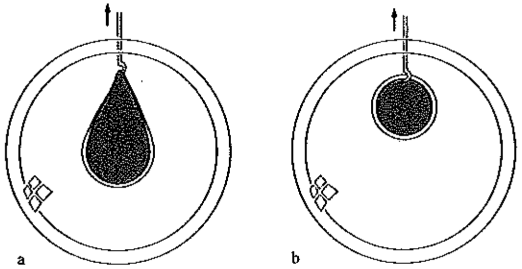


Fig. 7.31. **Visual assessment of the ability of the pupil to dilate**

a If the pupil is dilatable, locally applied forces tend to deform the pupil rather than displace it.

b The opposite effect is seen in a rigid, nondilatable pupil, which is displaced rather than deformed

7.32

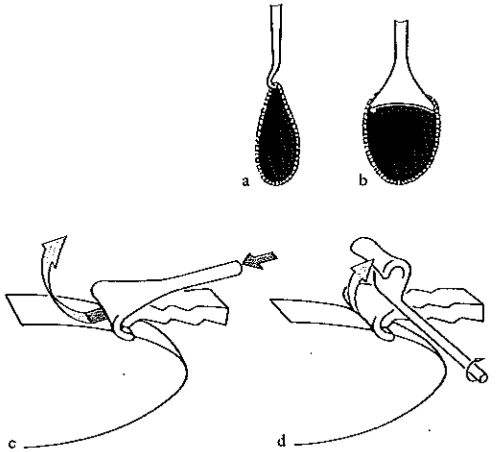


Fig. 7.32. **Iris hooks as retractors**

a Narrow hooks have small areas of contact with the lens and expose only a small field.

b Broad hooks expose a larger field. The large contact area with the lens increases the risk of capsule injury, but this can be reduced by shaping the hook surface to conform to the front surface of the lens (equal radii of curvature). This distributes the force evenly over the contact area and reduces pressure on the lens.

c Handle at right angles to the axis of curvature of the hook. To remove, the hook must be pushed back toward the pupil.

d Handle parallel to axis of curvature: The hook is removed by simple rotation of the handle

7.33

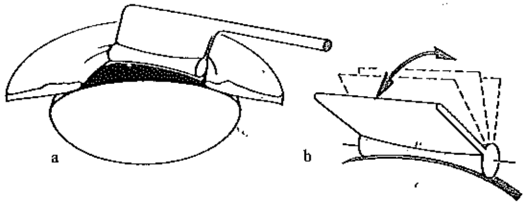


Fig. 7.33. **Rigid instruments as contact retractors**

a The lower surface of the rigid retractor conforms to the curvature of the anterior lens surface, ensuring full, uniform contact with the lens.

b Shaping the blade like a concave cylinder satisfies this condition at any angle of application

7.34

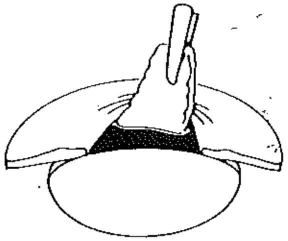
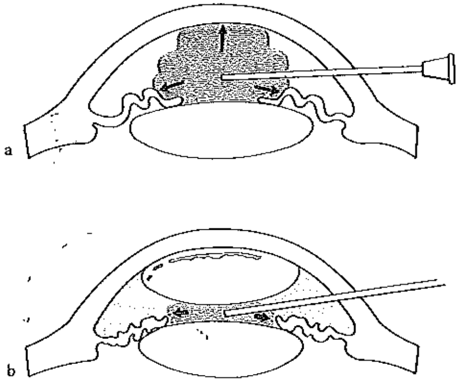


Fig. 7.34. **Sponge swab as an iris retractor.** Sponge swabs conform to the anterior lens surface when moist. They also adhere to iris tissue by suction and therefore can function as retractors. If the sponge absorbs aqueous, it expands and may endanger the corneal endothelium. If it becomes soft, its efficiency as a mechanical tool decreases

Fig. 7.35. **Viscomydriasis.** A "soft spatula" can be used to enlarge the iris aperture.

a The injection is directed toward the collarette rather than the pupil margin to ensure that viscoelastic material does not get behind the iris. *Note*: Because viscoelastic material may flow in all directions, a large amount may have to be injected, depending on the depth of the anterior chamber.

b The preliminary injection of an air bubble will reduce the amount of viscoelastic material needed. Once mydriasis has been accomplished, the air can be removed and replaced with watery fluid



applying *viscoelastic material* as a soft, permanent spatula (Fig. 7.35).

In *pathologic tissue* that is inelastic and immobile, the pupil must be enlarged by surgical incision. A *sphincterotomy* is sufficient when changes are confined to the iris sphincter.[11] **Multiple partial sphincterotomies** leave a portion of the muscle intact. They decrease but do not abolish its function (Fig. 7.36), so the pupil responds postoperatively to pupillomimetics and retains its normal shape.

If pathologic changes affect the *whole iris*,[12] the stroma must be incised to create an adequate opening. This will abolish pupillary function unless the incision is sutured. **Inferior iridotomies** (Fig. 7.37) are easy to perform but difficult to suture; they are used in cases where an unsutured iridotomy is acceptable.

Superior iridotomies are started from a peripheral iridectomy or parabasal iridotomy. The width of the initial iridectomy or iridotomy determines the width of the area that can be exposed by reflection of the iris flaps (Fig. 7.38).

When combined with iridotomy, multiple partial sphincterotomies may serve as relaxing incisions to aid in restoring a satisfactory pupil shape after suturing (Fig. 7.38e).

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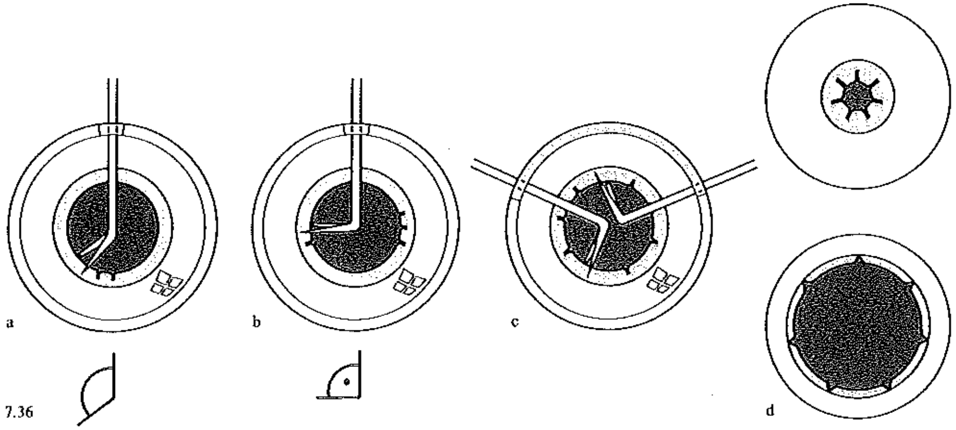
[11] As in senile or postinflammatory sclerosis or pseudoexfoliation syndrome.

[12] E.g., following iritis, acute glaucoma, or previous glaucoma surgery.



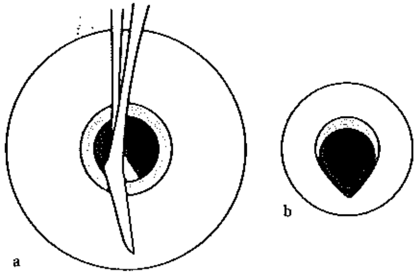


Fig. 7.37. **Inferior iridotomy**

a The iridotomy is cut downward from the pupil margin.

b The area exposed by a single incision is relatively small. Its width depends mainly on the retractility of the tissue

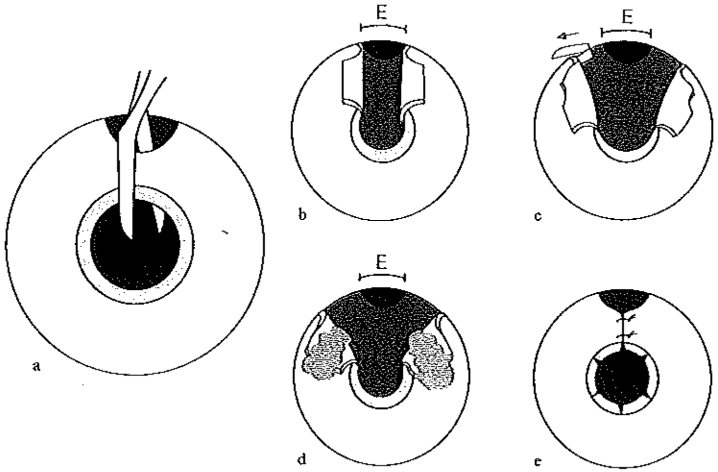


Fig. 7.36. **Multiple partial sphincterotomies**

a, b Sphincterotomies through a small corneal incision: Because the small opening makes it difficult to angle the instrument, the angulation of the microscissors determines the portion of the circumference that can be incised. Incisions at other sites require scissors with different angulations.

c With a large chamber opening, all the sphincterotomies can be made with a single instrument.

d Partial sphincterotomies preserve pupillary function while enabling mydriasis and miosis

Fig. 7.38. **Superior iridotomy**

a The deep scissor blade is introduced through a peripheral iridectomy, and the cut is made from there to the pupil.

b The width of the preliminary iridectomy (*E*) determines the exposure obtained by reflecting the iris flaps.

c In case of insufficient exposure the iris is incised along its root (*arrow*).

d Viscoelastic material can be used to effect and maintain reflection of the iris flaps.

e Closure of the iridotomy, shown here in conjunction with multiple partial sphincterotomies. *Note*: If the pupil is to retain a mydriatic response postoperatively, sutures should be placed only in the stroma, not in the sphincter itself

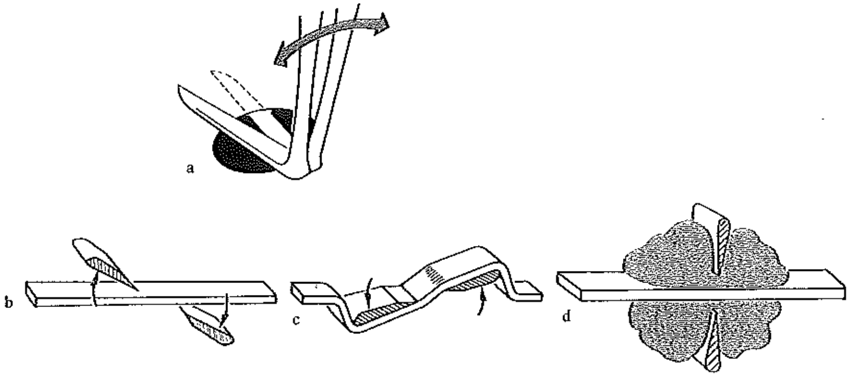


Fig. 7.39. **Controlling sectility in sphincterotomies and iridotomies**

a Iris mobility (friction between the scissor blades and tissue) as well as tissue tension can be controlled by tipping the scissors laterally.

b Friction is eliminated by holding the blades so that their sides are not in contact with the tissue. The blades are held in this position when advanced to the point of incision, their blunt edges leading to avoid tissue damage.

c Tipping the blades laterally brings their sides into contact with the tissue. This makes the tissue tense and increases friction. The blades are held in that position during the working motion (closure).

d Iris mobility can be reduced by embedding the tissue in viscoelastic material. The effect does not depend on the scissor position. Because forward shifting is neutralized, short microscissor blades can be used

The precision of iridotomies and especially of partial sphincterotomies is enhanced by applying techniques that minimize iris shifting by the advancing cutting point of the scissors (see Fig. 2.81). This can be accomplished by making the cut swiftly to exploit tissue *inertia*, by tilting the blades to fixate the tissue by *friction* (Fig. 7.39a–c), or by *viscoelastic immobilization* (Fig. 7.39d).

7.6 Repair of Iris Defects

The closure of iris defects is indicated not only on cosmetic or optical grounds[13] but also for surgical tactics. The tactical reason is to restore tension to the diaphragm to prevent anterior synechiae.

In iris tissue with normal mobility and compliance, most defects can be satisfactorily repaired by **approximating the margins** of the defect with simple interrupted sutures. Defects in rigid iris tissue must be repaired with **sliding flaps** mobilized by means of **relaxing incisions**. Relaxation may pose a dilemma, however, for it is antithetical to the goal of restoring diaphragmatic tension (Fig. 7.40). Thus, disinsertion from the iris root, while very effective for relaxation, should be avoided whenever possible. The peripheral iris suspension is preserved by placing the relaxing incisions at the pupil margin and in the iris stroma (Fig. 7.41). It is easier to control the degree of tissue advancement with multiple small incisions than with a few larger incisions.

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[13] Optical indications include the prevention of glare and monocular diplopia.

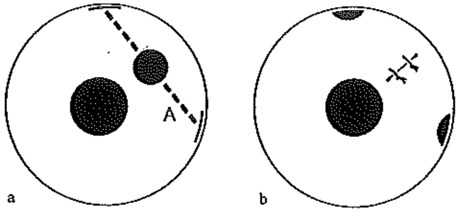


Fig. 7.40. **Closure of a stromal defect** (e.g., following excision of an anterior synechia)

a The stroma is mobilized by small peripheral iridotomies placed at the points where the imaginary transverse axis through the defect (*A*) intersects the iris root.

b Adjacent stroma is approximated over the defect with sutures. Compensatory defects are left at the iris root, but these cause no optical disturbances if in a very peripheral location

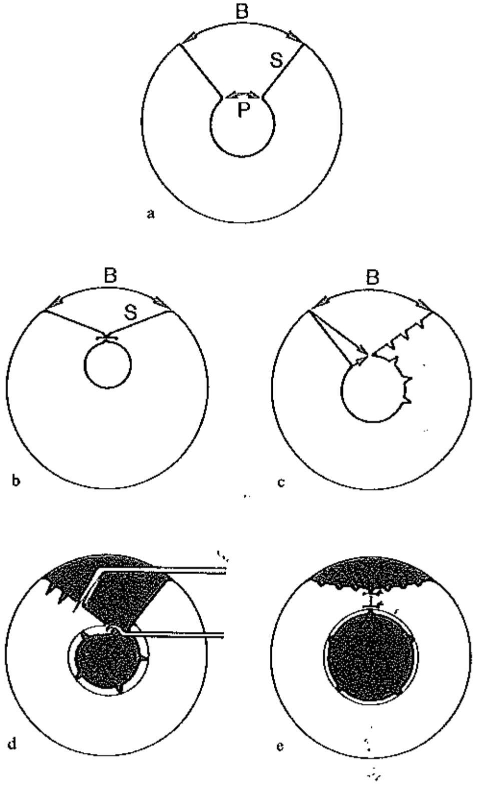


Fig. 7.41. **Closure of a sector iridectomy**

a Sector iridectomy in which a segment *B* has been removed from the base of the iris and a segment *P* from the pupil margin. For closure, the tissue advancement must compensate for these missing segments.

b An attempt to close the iridectomy directly with a suture at the pupil margin redirects the borders of the iridectomy (*S*) and shifts the pupil upward. Also, the pupil circumference is reduced by the distance *P*.

c If a rotation flap is created by lengthening S and the pupil margin, the pupil remains centered, and its suspension at the diaphragm remains intact. The tension is adjusted by using microincisions to lengthen the distance *S*.

d The necessary degree of relaxation is determined empirically by drawing the iris into the desired position with a small hook and making microincisions until the desired advancement is obtained.

e Closure with sutures

7.7 Suturing the Iris

Iris sutures are used for attaching

- *iris to iris* (closure of iridotomies or traumatic lesions; Fig. 7.45);
- *iris to iris root* (repair of iridodialysis; Fig. 7.47);
- iris to *foreign material* (e.g., fixation of implants; Fig. 7.44).

In a **transcorneal suture** the needle pierces the cornea in addition to the iris, so it must be very sharp and strong enough to overcome the corneal resistance.

In an **intracameral suture** the needle pierces only the delicate iris tissue, so a fine atraumatic needle with a round cross-section may be used.

The selection of suture type is influenced by the *width of the opening* in the anterior chamber. Transcorneal sutures can be placed as an independent procedure where otherwise no entry into the anterior chamber is planned; intracameral sutures are suitable only in cases where the anterior chamber has been widely opened. Suture selection is also influenced by the *condition of the iris tissue*. Sharp, heavy-gauge needles (i.e., for transcorneal sutures) can be used in normal tissue, for the defect produced by the needle will be smaller than the needle cross-section (owing to the centrifugal mobility of the resilient tissue). However, needles of this type will produce large defects in less mobile, pathologically altered tissue. Then, the size of the defect will at least equal the needle cross-section, and any lateral needle motion during suturing will cause an even larger rent. Thus, extremely fine needles (e.g., vascular needles) should be used to minimize trauma in pathologically altered iris tissue (i.e., intracameral sutures).

Sufficient *space* for suturing must be provided both anterior and posterior to the iris. *Air* injected into the anterior chamber may displace the iris posteriorly, obliterating the retroiridal space (Fig. 7.42a–c). *Viscoelastic material* placed behind the iris can expand and maintain the retroiridal space by displacing deeper tissues away from the danger zone (Fig. 7.42d).

The main *technical* difficulty in suturing the iris is the extreme *mobility* of the tissue. In practice this means that the *site of needle insertion* can be precisely defined by the surgeon, but the exact *site of emergence* is indeterminate, and this uncertainty must be allowed for in the suturing technique (Fig. 7.43). In the *transcorneal* suture, the insertion site is defined by an incision, while the site of emergence may lie anywhere on the cornea (Fig. 7.44). The needle for the *intracameral* suture, following its own trend of travel, is left to emerge into an undetermined portion of the anterior chamber and is then withdrawn from the chamber in a second step (Fig. 7.45).

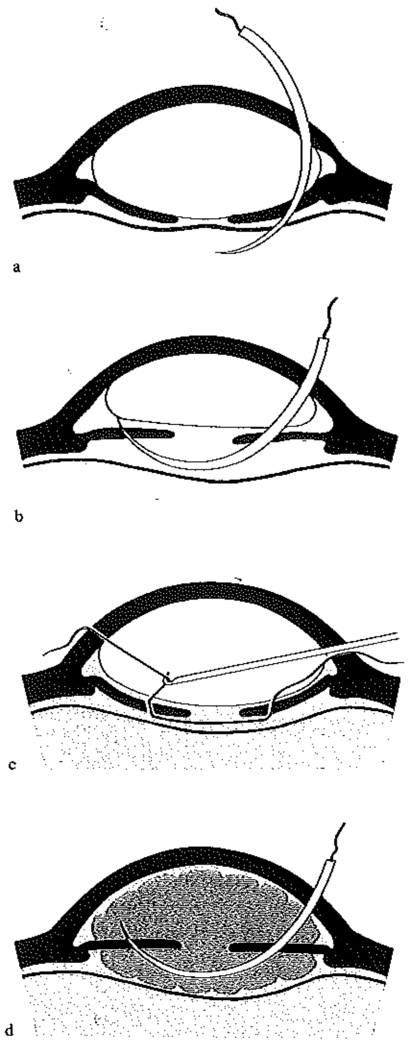


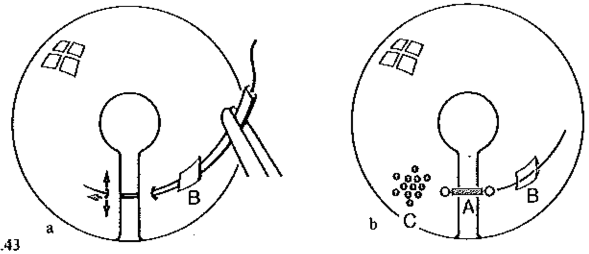
Fig. 7.42. **Space-tactical considerations in iris suturing. a–c air, d viscoelastic material**

a Maximum inflation of the anterior chamber with air presses the iris firmly against the anterior hyaloid. A suture needle passed behind the iris will enter the vitreous.

b Space for manipulations behind the iris is preserved by injecting just enough air that the bubble does not touch the iris. The remaining space within the chamber contains watery fluid.

c Once manipulations behind the iris are completed, additional air can be injected to make room for manipulations anterior to the iris (here: Retrieving the thread).

d Viscoelastic material can selectively expand the space behind the iris, creating the necessary space for pre- and retroiridal manipulations

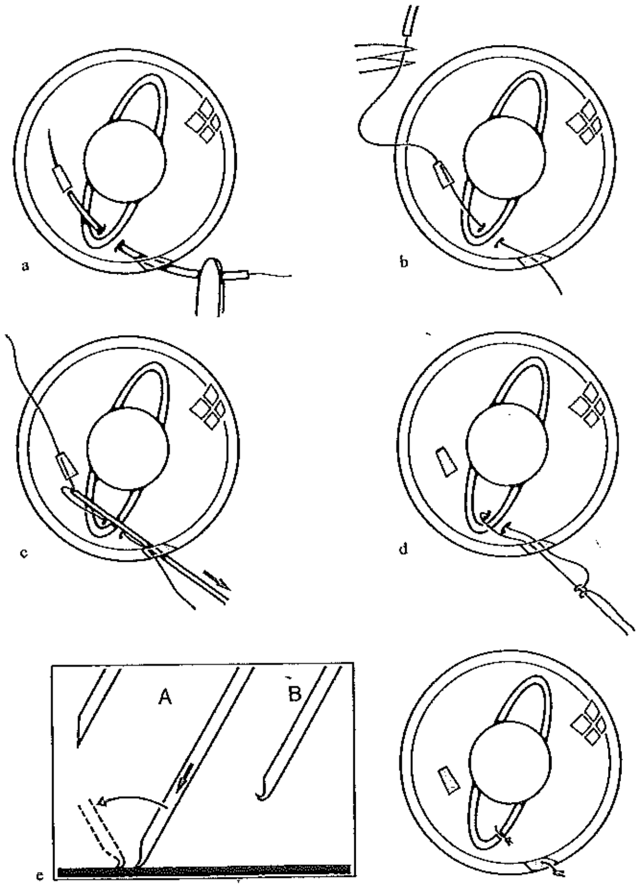


7.43

Fig. 7.43. Principle of suture technique

a Due to its extreme mobility, the iris may shift ahead of the tip (*arrows*) and the needle follows an unpredictable path.

b Parameters of the needle pathway: The distance between the planned entry and exit sites in the iris (*A*) is *given*. The site of needle insertion into the anterior chamber (*B*) is *selected* with the aim of reaching A, making proper allowance for the needle curvature. However, the exact site of emergence through the cornea (*C*) cannot be predicted and is *left to chance*



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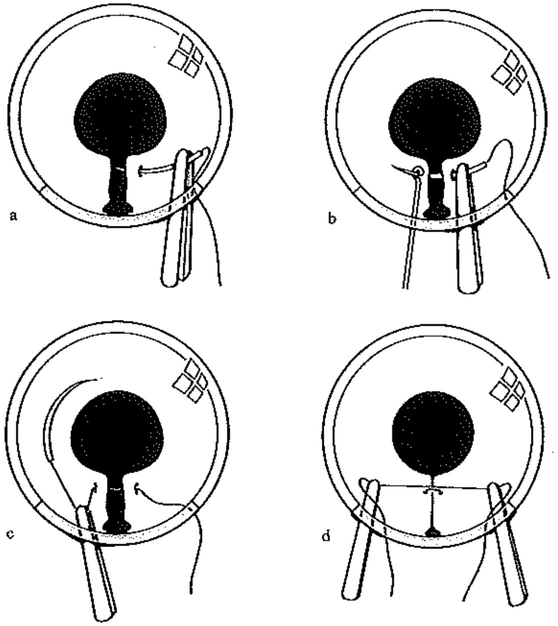


Fig. 7.45. Intracameral suture (illustrated for an iridotomy repair)

a Through a large corneal incision, a microneedle is introduced into the anterior chamber on a fine needleholder and passed through the limbs of iris. The anterior chamber is maintained by space-tactical means (e.g., viscoelastic material).

b If the resistance of the tissue and viscoelastic substance is not sufficient to keep the emerging needle tip from pushing the iris aside, additional resistance is provided by a second instrument. An iris hook used for this purpose increases the resistance all around the needle, and it can be easily removed.

c The needle is left in the chamber just as it emerges from the iris; it will stay suspended in the chamber if the latter has been filled previously with viscoelastic material. The thread is then grasped close to the needle eye with the suture forceps, and with the needle it is pulled backward out of the chamber.

d The knot is prepared outside the chamber and tightened inside the chamber

Fig. 7.44. Transcorneal iris suture (illustrated for the fixation of an IOL haptic to the iris stroma)

a A small corneal opening that is larger externally than internally (see Fig. 5.18D) is prepared. A long, heavy-gauge needle with sharp edges is passed through the opening, through the iris, and emerges somewhere on the cornea.

b The thread is cut from the needle.

c The thread is pulled back into the anterior chamber with a small, fine hook, and from there it is retrieved through the corneal incision. *Inset*: A very fine hook can be made by bending the tip of an injection cannula inward; this is done by rolling the tip on a hard surface. The hook is smaller than the diameter of the cannula, so it can be passed into and out of a small incision without snagging.

d The ends of the thread are tied into a slip knot and drawn tight over the haptic of the implant.

e The ends of the thread are trimmed, and the corneal incision is sutured if necessary (see hinge rule, Fig. 5.27)

7.8 Reposition of a Disinserted Iris

The procedure for repairing an iridodialysis depends on the length of the disinsertion and the compliance of the tissue. With a short iridodialysis and normal tissue structure, the iris can simply be repositioned and held in place with *viscoelastic material* until it becomes fixed in that position through scar formation.[14] With dialysis of rigid iris tissue,[15] greater forces will be needed to effect the reposition (*solid spatulas* and *iris hooks*). The iris may be reattached at its base by incarcerating it in the corneal incision or by using loops of thread. **Incarceration** leads to *shortening* of the intracameral iris surface and will cause *anterior displacement* of the diaphragm, depending on the location of the corneal incision (Fig. 7.46). **Suture loops** allow for precise guidance of the iris back to its normal anatomic position (Fig. 7.47; see examples in Figs. 7.48–7.50).

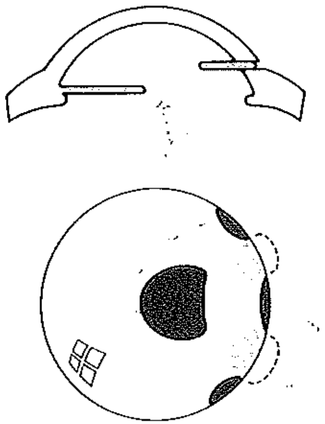


Fig. 7.46. **Reposition by incarceration of the iris root in a corneal incision.** An iris root incarcerated in a corneal incision lies farther peripherally than normal. It also lies far anterior to its natural position if the incision has been placed at the limbus

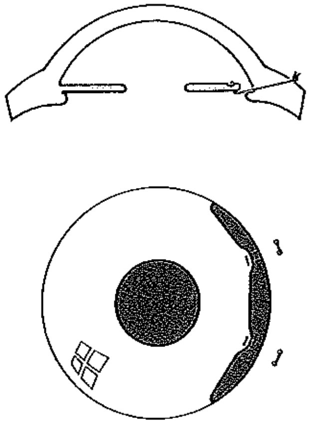
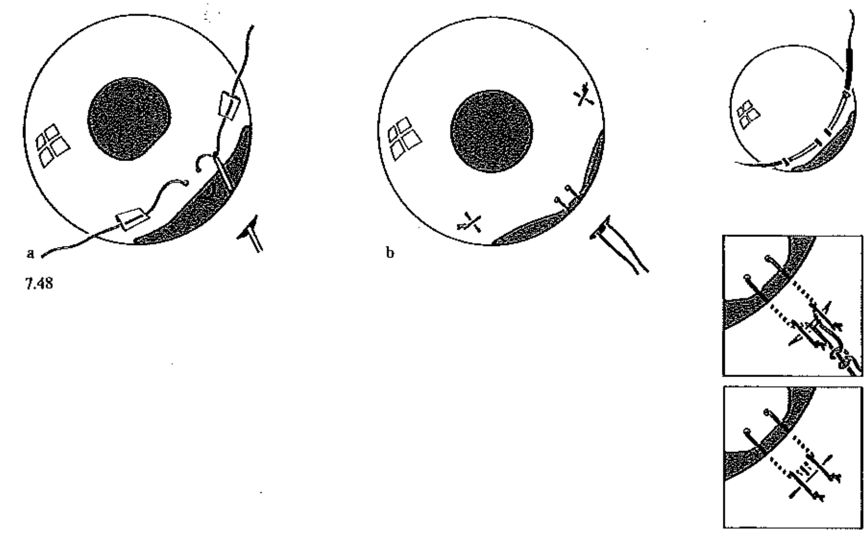


Fig. 7.47. **Iris reposition with sutures.** If the iris root is fixed with loops of thread, an essentially normal pupil shape can be achieved by fine adjustment of the suture tension. The threads can be passed well peripherally through the chamber angle to give an essentially normal anteroposterior iris position

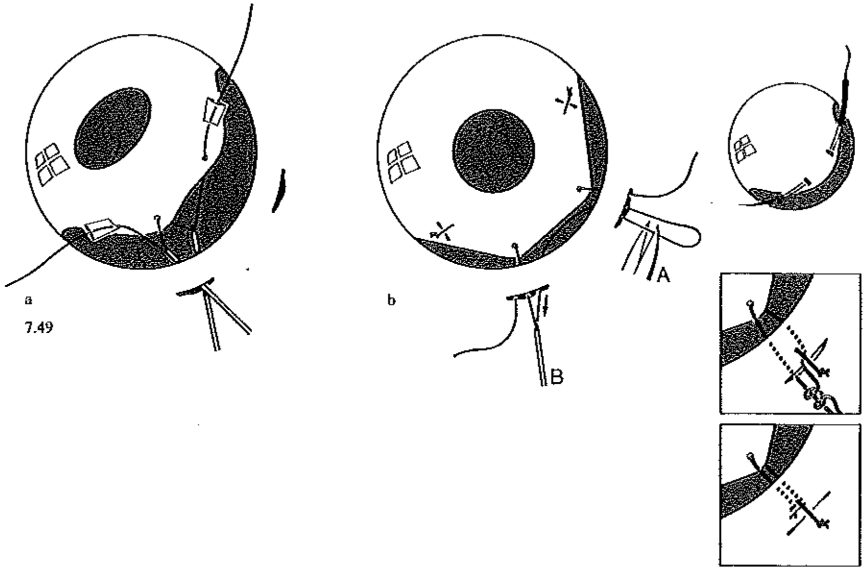


7.48

Fig. 7.48. Simple transcorneal iridodialysis repair

a After placement of the suture as shown in Fig. 7.44b, a third incision is made at the proposed fixation site behind the limbus. Both ends of the thread above the iris are brought out through the incision with a small hook.

b The iris is reapproximated to the periphery by traction on the protruding threads. Finally the incision is sutured so that the iris threads can be tied around the scleral sutures (*insets*)



7.49

Fig. 7.49. Repair of a longer iridodialysis

a Two (or more) scleral incisions are prepared as fixation sites. For each fixation one thread loop lying above as well as below the iris are brought out through the incisions.

b One exteriorized loop is cut (*A*) and pulled out through the second incision (*B*). Finally the loops are tied around the scleral sutures (*insets*)

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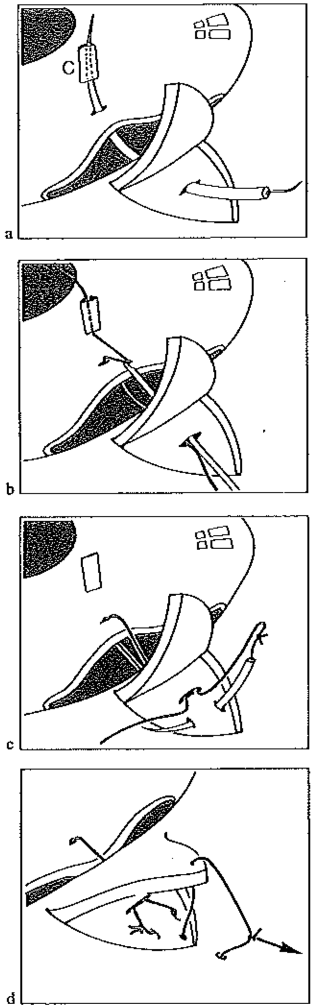
[14] "Viscoreposition" may suffice for a small, accidental iris avulsion occurring during surgery. Here the tissue is structurally normal, and there are no forces that might redisplace the repositioned iris. If this technique is unsuccessful, other obstacles should be suspected (e.g., vitreous prolapse) and managed accordingly.

[15] As in the secondary repair of an inveterate posttraumatic iridodialysis. *Note*: Often there are associated lesions (zonular rupture, retinal detachment, etc.) that must be recognized preoperatively and incorporated into the operating plan.



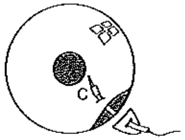


Fig. 7.50. Transcorneal iridodialysis repair using a partial-thickness scleral flap. This technique poses little risk of aqueous loss because there is a minimal opening for insertion of the needle and the retrieving cannula hook.

a A partial-thickness scleral flap is dissected at the limbus. The thinning of the tissue layer facilitates needle passage and enables the surgeon to locate the anatomically correct insertion site while visualizing the structures of the chamber angle through the thin scleral bed. The needle passes through the scleral bed, through the iris margin, and emerges somewhere on the cornea (*C*).

b The transcorneal suture segment is brought out through the incision as in Fig. 7.44c.

c With both ends of the suture protruding from the incision, one end is tied to the thread remaining on the needle, and the needle is passed through the floor of the thinned sclera.

d The ends of the iris suture are tied together, and the scleral flap is replaced and sutured

8 Operations on the Lens

8.1 General Problems of Surgical Technique

Cataract extractions may be performed in two ways: by removing the lens intact in its capsule (*intracapsular cataract extraction*) or by leaving a portion of the capsule in the eye (*extracapsular cataract extraction*) (Fig. 8.1).

From the standpoint of surgical technique, the lens behaves as a *pressure chamber* consisting of a closed capsular bag filled with a more or less fluid material. The effects of externally applied forces depend on the *capsular tension*. If the capsule is very tense, applied forces will be transmitted to the entire capsule system including the zonule, regardless of the site of application. But if the capsule is lax, the force will act mainly at the site of its application. Capsular tension is lowest when the capsule has been *breached*. Then the capsule no longer forms a pressure chamber, and forces are transmitted to the zonule only when applied close to the attachment of the zonular fibers.

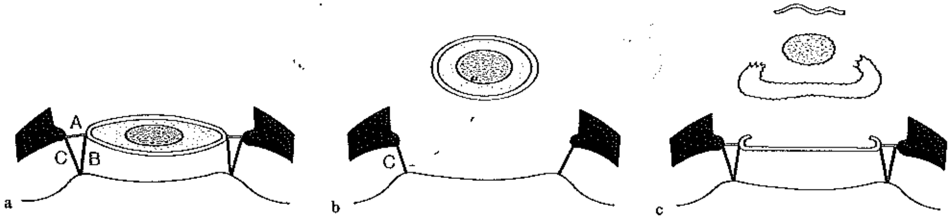


Fig. 8.1. Methods of lens delivery

a The normal lens is suspended by zonule fibers, some passing to the ciliary body (ciliocapsular ligament *A*) and some to the anterior hyaloid membrane (hyalocapsular ligament *B*). A third fiber system links the anterior hyaloid to the ciliary body (hyalociliary ligament *C*).

b In an intracapsular lens extraction, the lens is delivered intact. The hyalocapsular and ciliocapsular portions of the zonule are divided, leaving behind the hyaloid membrane with its hyalociliary fibers. It alone forms the anterior boundary of the vitreous chamber (see also Fig. 1.39).

c An extracapsular extraction leaves behind the lens capsule with all its zonular attachments, so there is less weakening of the anterior vitreous boundary. The lens components – the anterior capsule, cortex, and nucleus – are removed in separate maneuvers

From the standpoint of **spatial tactics**, the lens is considered *part of the vitreous chamber*. Therefore any manipulation on the lens affects the entire vitreous body, and all measures must be evaluated in terms of their overall effect. If the vitreous pressure is to remain constant, forces must be applied to the lens in such a way that their vector components are parallel to the vitreous surface (see Fig. 1.45b). Conversely, a deliberate change in vitreous pressure is produced by applying vector components perpendicular (centrifugal or centripetal) to the surface. Thus, shifting the lens horizontally does not alter the vitreous pressure, whereas lifting or depressing the lens is apt to cause pressure changes (Fig. 8.2).

A low vitreous pressure can be maintained only if the lens delivery is effected by traction (*extraction*). If the lens is removed by *expression*, a rise of vitreous pressure is inevitable since it forms the basis of the maneuver.

The **manipulations for lens removal** can be divided into several phases:

- *mobilization* of the lens by detaching it from structures that are to remain in the eye;
- *alignment* of the lens so that it can negotiate the pupil and incision;
- *locomotion*, i.e., delivery of the lens from the eye.

All these basic manipulations can be synthetized into a single action by the operator, but separating them into their individual components is useful in that it provides a greater *safety margin*: The force of the individual manipulations is smaller than that of the procedure as a whole, and the direction of the forces can be optimized for each step, making the maneuver easier to control.

The *objective* is to remove only the intended structures from the eye while leaving all other structures in place. Therefore, monitoring the tissues remaining in the eye is no less important than monitoring the parts that are to be removed. **Efficiency control** in lens removal is a matter of confirming that each applied force elicits an adequate, corresponding movement of the lens. Failure to elicit this movement is a warning sign that mechanical energy is being stored and may be released unexpectedly. **Safety control** in lens removal must ascertain that motion of the part to be removed does not elicit motion of parts that are to remain. Thus, the operator directs his attention not only toward the movements of the lens in response to his instrumentation but also toward the anatomic landmarks that confirm total immobility of the structures to be left behind.[1]

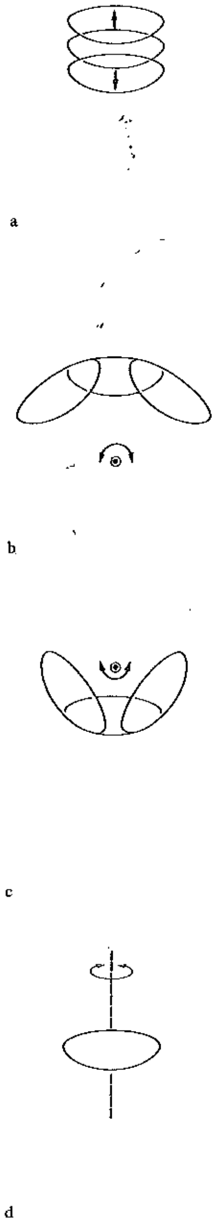


Fig. 8.2. **Space-tactical consequences of lens movements**

a Perpendicular (i.e., centrifugal or centripetal) vector components alter the vitreous volume, creating a positive or negative pressure.

b Movements along the vitreous face cause shifts of vitreous substance but do not affect its volume.

c Movements about the center of curvature of the posterior lens surface affect neither the shape nor the volume of the vitreous body.

d Rotational movements about the sagittal lens axis do not affect the vitreous shape or volume

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[1] In an *intracapsular* extraction, for example, attention is given to the iris position: If the iris retains its position during forward motion of the lens (i.e., "falls back into place"), this is a sign that the remaining parts of the diaphragm are not following the motion of the lens. In an *extracapsular* extraction, attention is given to the free margins of the incised lens capsule; these must remain stationary during motion of the lens nucleus and cortex.

8.2 Intracapsular Lens Delivery

In an intracapsular lens delivery, destruction of the diaphragm is controlled in such a way that only the zonular fibers that bridge from the capsule to the ciliary body and to the anterior hyaloid are divided. The *lens capsule* and *anterior hyaloid* themselves should remain intact.

8.2.1 Mobilization (Zonulolysis)

Destruction of the diaphragm is localized to the *zonule* by concentrating the applied forces (maximizing pressure) precisely at that site while distributing the forces as broadly as possible (minimizing pressure) over the *lens capsule*.

The forces may be transferred indirectly to the zonule via the lens capsule, or they may be applied to the fibers directly. An **indirect transfer** of forces during lens *expression* is accomplished by a general tensing of the diaphragm. In this case the site of zonular rupture may not coincide with the site of application of the expressing instruments, but depends on local variations in fiber resistance.

The forces in a lens *extraction* are transferred indirectly to the zonule by traction on the lens capsule (Fig. 8.3). The *force* necessary for the indirect rupture of the zonule depends on the capsular tension. The more lax the capsule, the greater the tension that must be supplied by the operator. Since the capsule becomes increasingly lax as division of the zonule proceeds, the amplitude of the lens excursions in an extraction should be steadily increased in order to transmit the necessary force (Fig. 8.3c).

Traction toward the pupil ("centripetal traction") exerts tension on *circumscribed fiber groups* and is effective for a localized rupture of the zonule (Fig. 8.4b, A'), although the amplitude of this maneuver is limited by anatomic constraints. *Traction by rotation* ("circumferential traction") has an unlimited amplitude (Fig. 8.4c, B'), but the tension affects all the fibers equally. Once an initial gap is created, though, the effect becomes localized as the fibers adjacent to the gap are ruptured first.

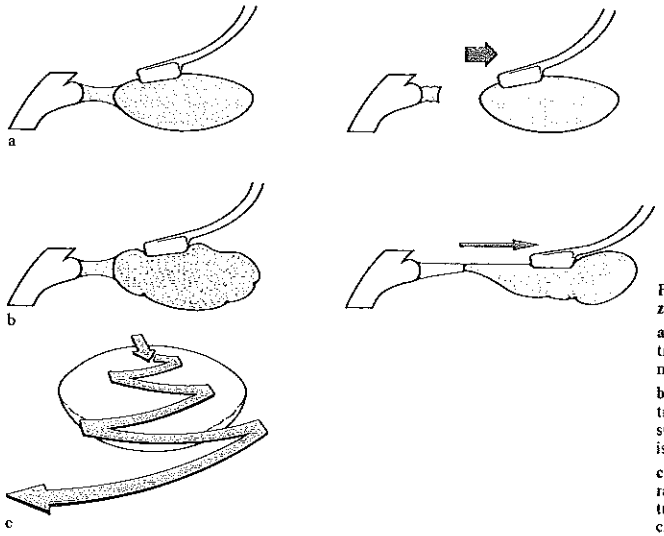

Fig. 8.3. **Applying indirect tension to the zonule**

a If the lens capsule is tense (*left*), little traction need be applied to the capsule to make the zonule fibers tense (*right*).

b If the capsule is lax (*left*), much greater traction is required, because first the capsule must be made tense before tension is transferred to the zonule (*right*).

c Since capsule tension dwindles as separation of the zonule proceeds, the amplitude of the traction must be gradually increased to compensate

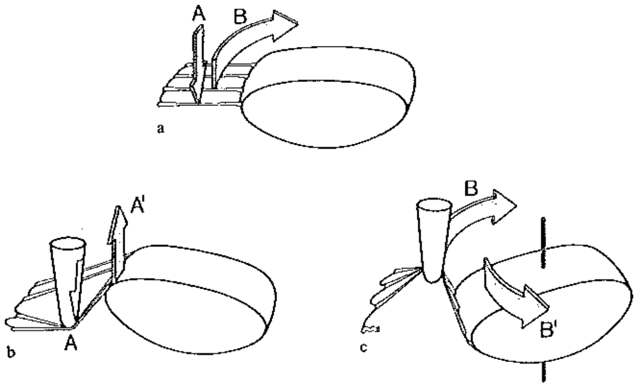

Fig. 8.4. Direct separation of the zonule

a Direction of fiber stretch: The fibers can be ruptured by overstretching them either perpendicular (*A*) or parallel (*B*) to the vitreous surface.

b The zonulotome can act perpendicularly by thrusting it into the zonule (*A*) or by elevating the lens (and thus the zonule) toward the stationary zonulotome (*A'*). Motion *A* produces force vectors directed toward the vitreous chamber, jeopardizing the anterior hyaloid. In motion *A'*, the zonule fibers are pulled away from the anterior hyaloid. This also creates a negative pressure in the vitreous space which retracts the anterior hyaloid from the danger zone and thus reduces the risk of hyaloid injury. The necessary depth of penetration of the zonulotome (*A*) depends on the compliance of the fibers, and this can be reduced by combining it with indirect primary tension (*A'*).

c The zonulotome can act parallel to the vitreous surface either by moving the instrument along the lens equator (*B*) or by rotating the lens about its sagittal axis (*B'*) to press the fibers against the stationary zonulotome. Large excursions are possible with no danger to the vitreous chamber.

Motions *A* and *B* affect only the fibers directly ahead of the zonulotome, while motions *A'* and *B'* tense the fibers indirectly and can produce primary tension over a large area

The **direct application** of forces allows a highly selective division of the zonule fibers. In this method the fibers are engaged directly with an instrument (zonulotome),[2] which stretches the fibers to the point of rupture in a direction perpendicular or parallel to the vitreous surface (Fig. 8.4a). *Perpendicular* vector components (Fig. 8.4b) affect the vitreous chamber. They can be minimized however, because perpendicular forces are necessary only for making the initial rupture in the zonule. Once this initial gap has been created, all the remaining fibers can be divided *parallel* to the vitreous surface (Fig. 8.4c).

The critical phase of the zonulolysis, then, is the creation of the initial gap. Once that has been accomplished, division of the fibers can proceed using maneuvers that no longer jeopardize the vitreous.

Chemical dissolution of the zonule with alpha-chymotrypsin[3] reduces the force necessary to effect delivery of the lens. However, a liquid enzyme is difficult to control both in its intended action and its side-effects.

The enzyme dose can be reduced by *combining* chemical zonulolysis with mechanical zonulotomy. For example, alpha-chymotrypsin may be injected to produce the initial zonule gap, whereupon the remaining fibers are ruptured mechanically with a zonulotome.

The enzyme is applied as close as possible to the elected site of action (Fig. 8.5). On completion of the zonulolysis (Fig. 8.6), residual enzyme and zonule debris are removed by irrigation of the anterior chamber. At this point the lens is in a subluxated condition.

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[2] Besides specialized instruments, an iris retractor (Fig. 8.18b) or even an expressor indenting the sclera (Fig. 8.16) can function as a zonulotome.

[3] Alpha-chymotrypsin is a proteolytic enzyme that dissolves the zonule fibers when applied in concentrations of 1:5000 to 1:10000. It acts in 1–5 min at a temperature of 25°–35° C; the waiting time depends in part on whether the enzyme is cold or warm when applied. It is inactivated by acids and alkalis, serum and blood, DFP and chloramphenicol (which can be used intraoperatively to inactivate the enzyme), detergents, disinfectants, alcohol (needles and cannulas must contain no residues from these substances and must be heat-sterilized), and temperatures above 40° C. The enzyme preparation is sterilized by filtration only. No preservatives may be added. For this reason, only fresh solutions should be used to reduce the risk of contamination.

The major reported side-effect of alpha-chymotrypsin is a postoperative rise of intraocular tension. There are also reports of corneal damage if the endothelium is disrupted, hyaloid membrane damage, and retinal morbidity if the enzyme enters the vitreous.

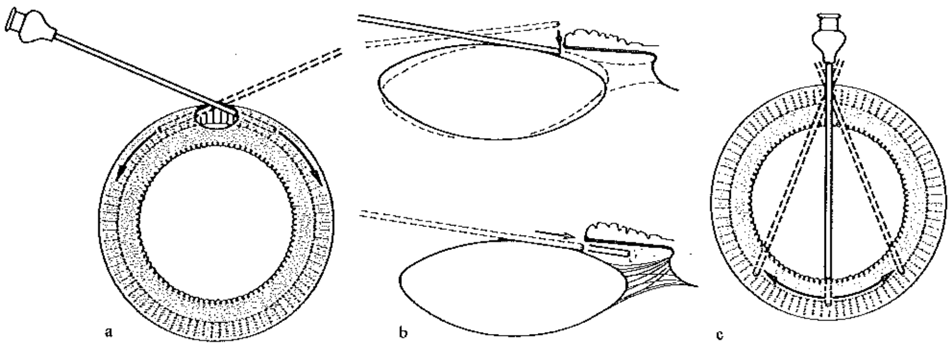

Fig. 8.5. Application of zonulolytic enzyme

a To apply the enzyme directly to the zonule, it is injected behind the iris. The upper circumference of the zonule is accessible through a peripheral iridectomy.

b The lower circumference is reached by crossing the pupil. Lens damage is avoided by keeping the cannula raised away from the lens until the opposite pupil margin is reached. Once there, the cannula tip is lowered and is then passed beneath the iris (*above*); it is always directed tangentially away from the anterior lens surface. So the tip of the cannula does not come in contact with the lens capsule (*below*).

c The enzyme is distributed along the lower zonule with a sweeping movement of the cannula

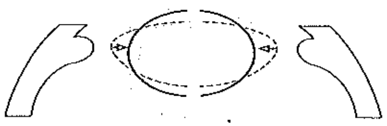

Fig. 8.6. Confirmation of total zonulolysis. When all the suspensory fibers of the lens have been divided, the lens acquires a more spherical shape (*red arrows*). It may also move outward if there is a slight vitreous overpressure, or it may sink inward from its own weight if the hyaloid membrane is lax (*white arrows*)

8.2.2 Aligning the Lens for Delivery

By deciding which *pole* of the lens will lead the delivery, the operator establishes the site for making the *initial gap* in the zonule (Fig. 8.7). That site will determine whether it is technically more convenient to tamponade the gap during the delivery or leave it open.[4] In addition, the lens alignment determines the *relationship between the lens cross-section and the cross-section of the*

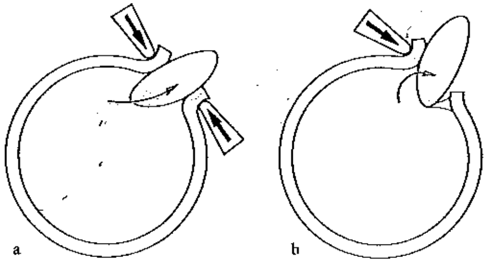

Fig. 8.7. Lens alignment during delivery

a Sliding: The superior pole of the lens emerges through the pupil and incision first. There are gaps in the incision side of the zonule as well as in the opposite side. Tamponade is difficult because it must involve both lips of the incision.

b Tumbling: The inferior pole of the lens emerges first. The initial gap is on the inferior side, and from that point separation of the zonule progresses toward the corneal opening. Tamponade is easier because only the superior lip of the incision needs to be controlled

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[4] Sealing the zonule gap or leaving it open affects the pressure in the vitreous chamber during the delivery; see Figs. 8.10 and 8.11.

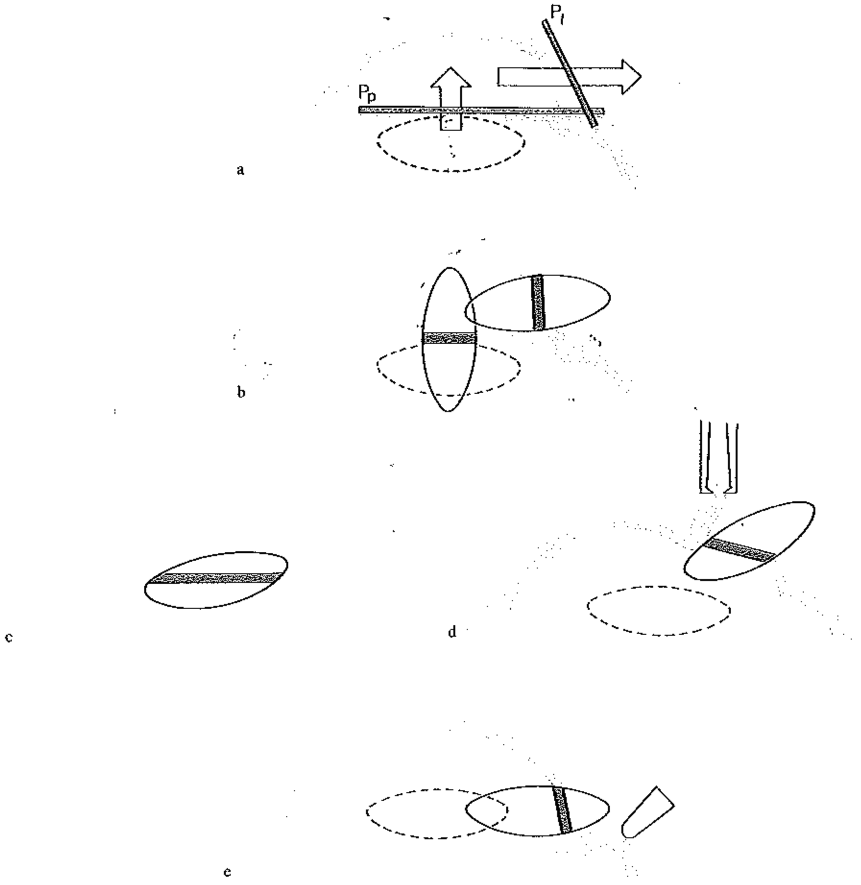

Fig. 8.8. Criteria for lens alignment during delivery: Relationship of the lens to the pupil and incision

a The lens first moves vertically upward into the anterior chamber, traversing the pupil, and then horizontally outward, traversing the incision. The angle between the plane of the pupil (*Pp*) and the plane of the incision (*Pi*) is nearly 90 degrees.

b If the lens is to present a minimum cross-section to both openings, it must be rotated approximately 90°.

c This rotation can be reduced if the pupil is very large, as this allows the lens to traverse it with a larger cross-section.

d The rotation can also be reduced by raising the superior lip of the corneal incision. *Note*: This maneuver creates a corneal hinge fold.

e Rotation of the lens can be avoided by depressing the lower lip of the corneal incision, thereby reducing the vertical component of the delivery. *Note*: This creates a hinge fold in the sclera (not in the cornea), which may affect the vitreous pressure

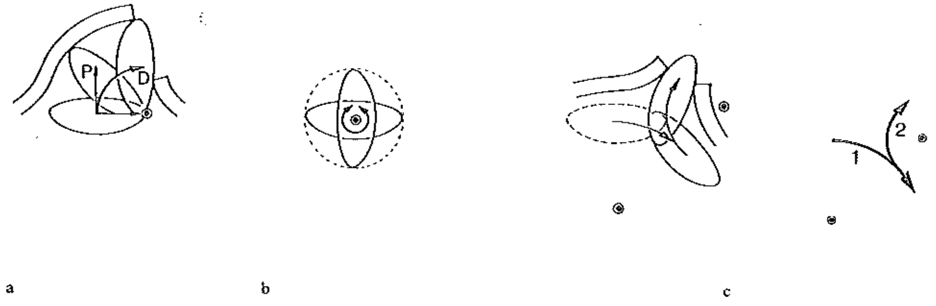

Fig. 8.9. Center of rotation in various tumbling maneuvers

a Tumbling the lens about an axis through its superior pole: The rotary movement (*D*) produces a vector component (*P*) perpendicular to the vitreous chamber. The lens presents its largest cross-section when traversing the pupil and incision.

b Rotation of the lens about its transverse axis. A spheroidal lens can be rotated in any direction, analogous to a spheroidal joint in a socket. The less spherical the lens, the greater the shift of vitreous substance caused by its rotation.

c Reverse tumbling about extralenticular points. Tumbling in two phases: *1* Rotation of lens about the "center" of the vitreous (analogous to Fig. 8.26). *2* Rotation about the center of curvature of the posterior lens surface (analogous to Fig. 8.2c). In this technique the lens presents its smallest cross-section to both pupil and incision

opening as the lens traverses the pupil and the corneoscleral incision. This in turn determines the resistance to the delivery and the degree of force that must be applied.

Because the planes of the pupil and the corneal incision are nearly at right angles to each other, the lens must be rotated almost 90° in order to negotiate both openings with a minimum cross-section (Fig. 8.8a, b). The necessary degree of *lens rotation* can be reduced by modifying the openings, i.e., changing their size to accommodate a greater lens diameter (Fig. 8.8c) or repositioning them onto the path of the emerging lens (Fig. 8.8d).

In delivery by sliding, the lens is oriented so that the *pole closest to the incision* is the first to emerge. Therefore the *initial zonule gap* is made directly below the incision (although additional gaps may form elsewhere as a result of contralateral zonule tension). The lens presents a *relatively large cross-section* on traversing the pupil (Fig. 8.8c), so adequate mydriasis is required. The movements of the lens can follow the vitreous surface (Fig. 8.8e), so there is little or no effect on the vitreous volume.

In delivery by tumbling the *opposite pole* is the first to emerge through the incision. Consequently the *initial zonule gap* is made on the side opposite the incision. The ipsilateral zonule may remain intact almost until completion of the delivery. Because of its rotation, the lens can present an optimum cross-section as it traverses the pupil. Deformation of the vitreous can be minimized by guiding the lens along the vitreous surface in all maneuvers. Success in achieving these goals depends on the *axis* of lens rotation during the tumbling maneuver. If the lens is tumbled about an *axis at its upper pole*, it will present a large cross-section to the pupil and incision.[5] It moves away from the vitreous, whose pressure is correspondingly reduced (Fig. 8.9a). Tumbling the lens about an *intralenticular axis* exerts mass effects on the vitreous which can raise its pressure and increase resistance to the tumbling maneuver (Fig. 8.9b). In delivery by *reverse tumbling*, the lens is rotated about two extralenticular axes in two separate stages.[6] Neither movement significantly affects the vitreous volume, regardless of the shape of the lens (Fig. 8.9c); the lens can present a minimum cross-section for traversing the pupil and incision.

8.2.3 Locomotion

Locomotion would require very little force if performed in isolation, but it is invariably combined with concomitant maneuvers (zonulolysis, lens alignment) which dictate the *force* needed for the delivery. If the zonule has been completely separated (e.g., by chemical zonulolysis) and the pupil and incision are sufficiently large, minimal force need be applied.

The forces used for the delivery (the "motors") are either *pressure* (expression) or *traction* (extraction). In delivery by **expression**, the lens is expelled from the eye by

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[5] Although it touches almost the whole posterior surface of the cornea in this maneuver, an intact lens produces relatively little endothelial trauma. The main danger is contact with the extracting instrument (e.g., capsule forceps), the most vulnerable area being the stiffened tissue at the hinge fold.

[6] Reverse tumbling can be compared to the backing of an automobile.

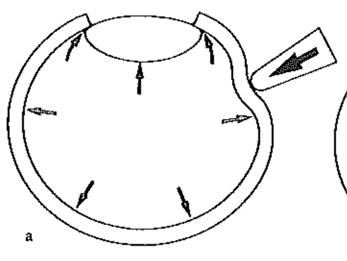

Fig. 8.10. Pressure as a motor for lens delivery (expression)

a The pressure is increased by deformation of the vitreous chamber. If the lowest resistance is in front of the lens, the lens will be expressed.

b If the lowest resistance is elsewhere, extralenticular tissue will protrude when the pressure is increased (e.g., vitreous prolapse due to inadequate tamponade)

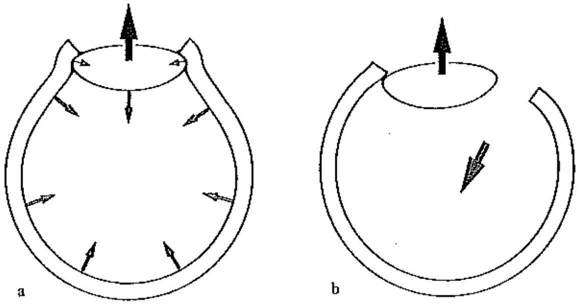

Fig. 8.11. Traction as a motor for lens delivery (extraction)

a Traction on the lens creates a vacuum in the vitreous chamber which holds the lens back and hinders delivery.

b Gaps next to the lens allow pressures to equalize

pressure from the anterior hyaloid. The necessary pressure rise in the vitreous chamber is produced by deforming the vitreous with instruments (expressors). As shown in Figs. 1.42c and 1.43c, the site of application of the expressors is immaterial in terms of the pressure that is produced. Their placement is determined only by considerations of resistance control: the *resistance* must be low in front of the lens itself (to clear a path for the delivery) but high over all other parts of the diaphragm (tamponade). If there are zones of low resistance adjacent to the lens, the anterior hyaloid will bulge forward at those sites while the lens itself remains stationary (Fig. 8.10).

Delivery by **extraction** is accomplished by *traction to the lens*. This may induce an expansion of the vitreous space and a negative vitreous pressure. As this tends to draw the lens backward, the *pressures must be equalized* before the extraction can proceed.[7] This requires openings in the diaphragm (iridectomy, gaps in the zonule) through which fluid and air can shift from the anterior chamber to the vitreous compartment (Fig. 8.11).

A major difference between the two methods is that open gaps in *expression* are a source of complications (by allowing pressures to equalize) and must be tamponaded during the delivery. In *extraction* they are essential for smooth conduct of the maneuver, and the operator must create such gaps and keep them open throughout the delivery.

The *degree of force* that can be applied is limited by the resistance of the anterior hyaloid in *expression* and by the solidity of the lens capsule in *extraction*. Both structures are liable to rupture if the progress of the delivery is impeded. It is essential, therefore, that obstacles to the delivery be promptly identified and cleared. The early recognition of these obstacles may rely on tactile or visual feedback. The major *tactile* warning sign is an increase of resistance manifested as an increasing force needed for the delivery; the major *visual* sign is a paucity of lens motion. If the lens does not respond to an *expression* maneuver despite increasing pressure, any further pressure increase will only exacerbate the risk of vitreous prolapse. If the lens is not moved by an *extraction* maneuver, increasing the traction may rupture the capsule.[8]

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[7] The negative pressure can also cause iris pseudorigidity by holding the iris so tightly against the lens that delivery becomes impossible. Unlike true iris rigidity, which is manifested preoperatively by a persistent failure of mydriasis, pseudorigidity is relieved at once when pressures are equalized.

[8] The site of the obstruction is indicated by the direction of the traction folds in the capsule ("arrows pointing to the obstruction").

8.2.4 Instruments for Lens Delivery

Expressors

The vitreous pressure necessary for lens expression is produced by *indenting the ocular wall* with a blunt instrument, the expressor (Fig. 8.12). The shape of the expressor is unimportant in terms of the vitreous pressure increase.[9] However, the instrument shape is significant for secondary functions: Expressors with a *small contact area* behave as sharp instruments and can be used as "zonulotomes"; expressors with a *large contact area* can tamponade the expanding gap in the zonule.

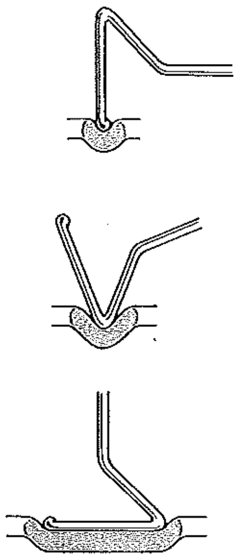

Fig. 8.12. Expressors. The scleral indentation (*pink*), the actual "expressor," is always larger and blunter than the instrument making the indentation. By proper application of the instruments it is possible to modify the area of contact and thus the "sharpness" of the expressor (here: A squint hook)

Forceps for Grasping the Lens Capsule

Forceps grasp the lens by making a *fold* in the capsule (Fig. 8.13). To make this fold, the forceps jaws must be pressed firmly against the capsule so that friction will prevent slippage during closure of the blades. The jaw pressure should be distributed evenly along the grasping surface to avoid capsule damage.

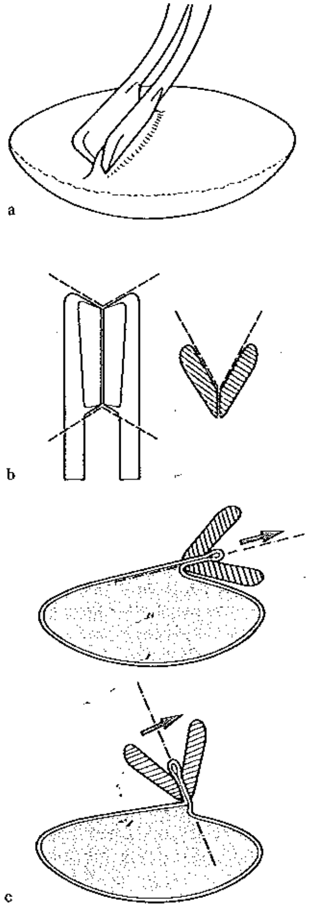

Fig. 8.13. Forceps for grasping the lens capsule

a The lens is grasped by a fold in the capsule.

b Jaw design: To ensure a uniform pressure distribution, the opposing surfaces should be flat and smooth and their edges carefully rounded. When the jaws are closed, they should meet evenly for their full length (stabilization of grasping pressure, see Fig. 2.8). The jaws are designed to diverge where not in direct contact with the capsule to reduce the danger of inadvertent grasping of neighboring tissue (e.g., the iris).

c Position of jaws during traction. *Above:* When the fold is pulled so that its axis (*hatched line*) is parallel to the direction of pull, only the blunt grasping surfaces of the jaws act on the capsule, not the edges. *Below:* But if the fold is pulled at an angle, one edge behaves as a sharp instrument and may damage the capsule

Erysiphake

The erysiphake consists of a suction cup in which a *vacuum* is created to fix the lens to the extraction instrument.

The interior of the cup is designed to exert a firm grip on the lens capsule while preserving its integrity (Fig. 8.14). As the anterior capsule partially prolapses into the cup, the whole capsule becomes tense and, with it, the zonule. The instrument is applied with just enough pressure to seat the entire rim of the cup firmly against the capsule surface.

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[9] In former times some surgeons even used their finger as an expressor – a method that affords excellent tactile feedback.

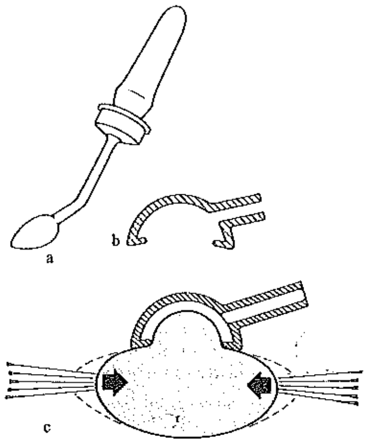

Fig. 8.14. **Erysiphake**

a Erysiphake with suction cup.

b Longitudinal section of suction cup. The rim is broad and shaped to conform to the lens surface so that it will not act as a cutting edge when suction is started. Its edges are well rounded. The size of the cup should be such that the capsule does not touch the inside of the cup or the vacuum tube, because the occlusion would occur at the wrong site and this would degrade the suction.

c The suction produces a general tensing of the zonule fibers

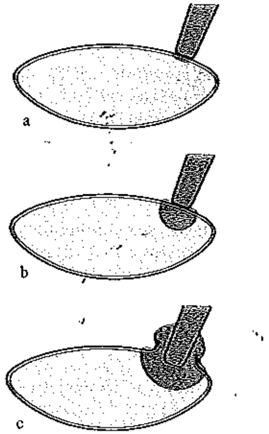

Fig. 8.15. **Cryoextractor**

a Superficial ice formation: Encompasses only the capsule.

b Large ice ball: Extends deep into the lens, encompassing the cortex and nucleus.

c Obliteration of a capsule lesion by a large ice mass

Cryoextractors

Cryoextractors form an adhesion with the lens by means of an *ice ball* that encompasses both the instrument and the tissue. Fixation is best when the ice ball extends deeply into the lens and does not tax the tensile strength of the capsule alone (Fig. 8.15b). Even if the capsule is damaged, complete extraction is still possible if all edges of the lesion can be encompassed by the ice mass (Fig. 8.15c).

The size and shape of the ice ball depend on the *shape*, *temperature* and *cold capacity* of the cryoextractor, i.e., on instrument characteristics that are predetermined in a given case. The size of the ice ball also depends on the *thermal conductivity* of the biologic media and thus on the fluid content inside and outside the lens. Differences in thermal conductivity can allow the selective cryoextraction of a lens in a liquid film within the anterior chamber or in the fluid vitreous, since the ice ball forms more rapidly in the solid lens than in the ambient fluid.[10] On the other hand, if the lens contents are highly liquid (as in intumescent cataract), the ice ball forms only superficially in the drier lens capsule, and there is an increased risk of capsular rupture (Fig. 8.15a).

Criteria for the Use of Extractors

The selection of an extraction instrument is based on its intrinsic volume, its contact area, and the lens deformation caused by the grasping mechanism (Table 8.1).

The instrument **volume** that may be introduced into the anterior chamber depends on the margin of deformation (depth of anterior chamber, vitreous pressure), for if the instrument is too bulky, the lens must be pushed toward the vitreous to prevent corneal damage, thereby *raising the pressure* in the vitreous chamber.

The **area of tissue contact** has a significant bearing on the risk of *capsule rupture*. If the extractor behaves as a sharp instrument, it will tend to rupture the capsule rather than the zonule. The contact area further affects the *intrinsic mobility* of the lens. If the contact area is small ("point fixation"), the lens can change its position ideally in response to all applied forces from the surgeon and from the zonule. If the contact area is large, the surgeon's actions are transmitted more rigidly to the lens and indirectly to surrounding structures.

The **pressure** that the instrument exerts on the lens during grasping also raises the vitreous pressure and therefore must be opposed by adequate resistance from the zonulocapsular diaphragm. If the latter is damaged (e.g., by a subluxated lens), instruments with a very low grasping pressure must be used.

Deformation of the lens on grasping is possible within the limits imposed by its ratio of volume to surface area. If the lens is almost spherical (as in intumescent cataract), any deformation leads to a general rise of capsule tension that may contraindicate the use of deforming instruments for grasping.[11]

Table 8.1

	Forceps	Erysiphake	Cryoextractor
Space in anterior chamber occupied by instrument	small	very large	depends on quality of insulation (i.e. on danger of freezing surrounding tissues)
Area of contact with lens	small	very large	depends on size of ice ball
Pressure on lens during grasping	high	low	negligible
Deformation of lens during grasping	considerable	depends on extent of prolapse into suction cup	negligible

8.2.5 The Phases of a Lens Delivery

Lens delivery is a continuous process in which the basic maneuvers of *mobilization*, *alignment*, and *locomotion* take place concurrently and in succession. For practical purposes, however, the delivery can be divided into four main phases according to the type of force applied:

1. Application of the instruments
2. Formation of the initial gap in the zonule
3. Passage of the lens through the pupil and incision
4. Final phase

1. In the initial phase of **instrument application**, the applied forces serve only to *engage the lens* with the delivery instrument. The degree of force depends on the type of instrument used (see Table 8.1).

2. During **formation of the initial gap** in the zonule, the applied forces serve to **initiate a rupture of the zonule fibers**. Locomotion is limited to the degree necessary to make the fibers tense. If a zonulotome is thrust toward the vitreous to rupture the fibers, the vitreous pressure will rise. But if the lens is lifted and the zonule drawn past a stationary zonulotome, a negative pressure results which draws the hyaloid membrane back from the initial gap (see Fig. 8.4b). The presence of this gap is essential for the next maneuver to proceed smoothly.

3. **Passage of the lens** through the pupil and incision constitutes the *main phase of the delivery*, for it is now that most locomotion occurs and the lens is freed of its remaining zonular attachments. Consequently the *greatest forces are needed* during this phase. The *direction* of force application depends on the mode of delivery: perpendicular forces are appropriate for expression but are strictly avoided in all other maneuvers. The *nature* of the applied force (pressure or traction) determines whether the developing gaps in the zonule should be left open or tamponaded.

4. The **final phase** begins as soon as the *largest lens cross-section* has passed through the corneal incision. At that point the lens will no longer fall back through the incision when locomotive forces are discontinued, and the delivery is practically complete. The forces can be reduced to the minimum necessary for dividing the few remaining zonular fibers. This reduction of forces acting on the vitreous chamber is an important safety factor during the final phase, when the vitreous is contained only by the highly vulnerable anterior hyaloid.

The techniques described below illustrate how the foregoing principles can be combined in practice to accomplish the lens delivery.

Expression

When the lens is delivered purely by expression, as noted above, the vitreous chamber is deformed by expressors, and the resulting pressure increase is used to initiate and control a prolapse of the lens (Fig. 8.16). The main problem is the potential for unintended prolapses.

The initial gap in the zonule is produced bluntly and thus with relatively large forces. This maneuver is most successful when the lens is almost spherical. Such a lens can be rotated in any direction without affecting the vitreous volume (see Fig. 8.9b), and this permits extensive stretching of the zonule. A voluminous lens also leaves a large margin of deformation in its wake, reducing the risk of vitreous prolapse.[12]

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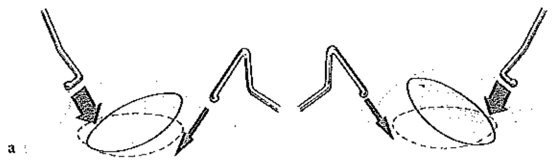
[10] This also applies to the zonule, which freezes more quickly than the fluid film that fills its interspaces. The danger of inadvertent inclusion of the zonule in the cryoextraction is greatest when the instrument tip is applied near the lens periphery. This can be difficult to detect visually if the zonular interspaces remain transparent.

[11] Because forceps must raise a fold in order to function, they can be used only on lenses whose capsular tension is low. If forceps extraction is attempted on an intumescent lens, the forceps will either skid off the lens surface or rupture the capsule.

[12] This suitability of spherical lenses for delivery by expression may explain why Smith's expression technique was so successful in India but commonly failed elsewhere. The cataractous lenses of Indians are often large and spherical.



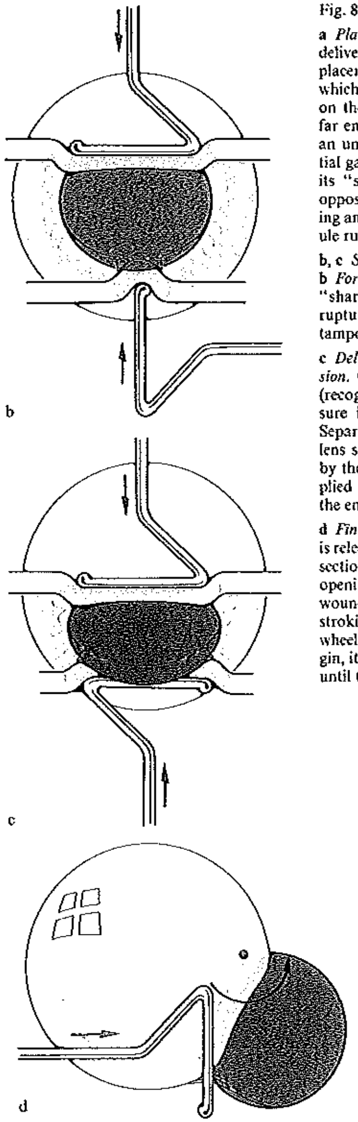


Fig. 8.16. **Expression**

a *Placement of instrument* (*left*: Sliding delivery; *right*: Tumbling delivery). The placement of the expressors determines which pole will emerge first. The expressor on the side of the leading pole is placed far enough from the lens border to allow an unrestricted delivery. It forms the initial gap in the zonule, so it is applied with its "sharpest" point (*small arrow*). The opposite expressor keeps the lens from rising and is applied "bluntly" to avoid zonule rupture at that site (*large arrow*).

b, c *Sliding technique.*
b *Formation of initial gap.* The upper, "sharp" expressor is pressed inward to rupture the zonule and simultaneously tamponade the resulting gap.

c *Delivery of lens through pupil and incision.* Once the leading pole has emerged (recognized by its free border), the pressure is increased to induce locomotion. Separation of the zonule proceeds as the lens slips past the scleral bulge produced by the upper expressor, which now is applied over a broader area to tamponade the enlarging zonular gap.

d *Final phase.* All pressure on the vitreous is released as soon as the largest lens cross-section has passed through the corneal opening. The delivery is completed and the wound simultaneously closed by gentle stroking with the expressor. If the lens is wheeled out over the opposite wound margin, it will tamponade the corneal opening until the delivery is completed

A major advantage of delivery by expression alone is that *no instruments* need to be introduced into the anterior chamber. *Partial expression* achieves a similar tactical goal while reducing the risk of vitreous prolapse. In this method the lens is expressed only until its upper pole presents in the incision. There it is grasped with an extraction instrument and the delivery completed by a combined technique (expression and extraction).[13]

Combined Extraction and Expression

If both pressure and traction are employed for lens delivery, the surgeon can select the most favorable "motor" for a given situation. *Traction* relieves stress on the vitreous and is indicated if there is a threat of *prolapse*. *Pressure* relieves stress on the lens capsule and is used if there is a threat of *capsule rupture*. It is important to note, however, that a rapid change between traction and pressure requires a correspondingly rapid adjustment in the management of the resulting zonule gaps (see Figs. 8.10, 8.11).

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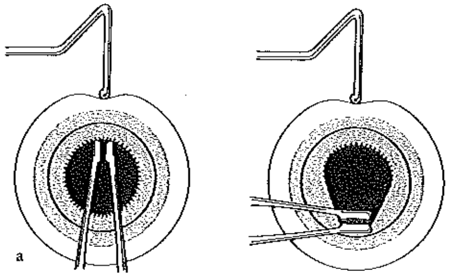
[13] If the emerging lens is grasped with a cryoextractor, care is taken not to freeze the zonule at its attachment. Whether or not the emerging pole of the lens is still attached to the zonule is judged by the curvature of the area between the lens and pupil margin. The surface of a lens still attached to the zonule extends flat toward the iris, and the pupil follows the lens movements. Conversely, a lens free of zonules presents a sharp curvature, and the pupil margin recedes on motion of the lens.



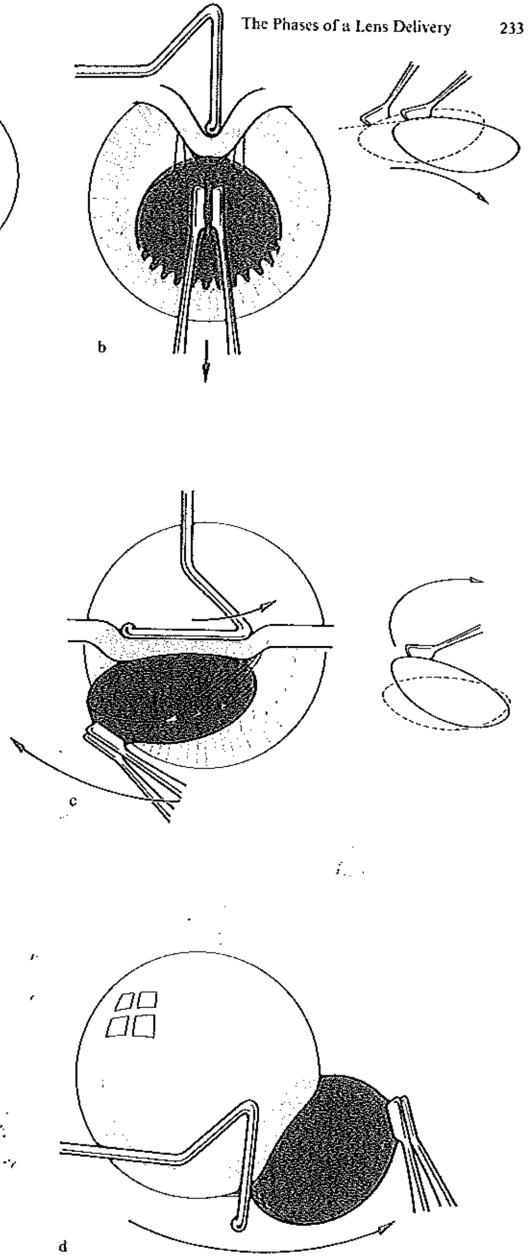


Fig. 8.17. Combined expression and extraction (forceps)

a *Placement of instruments.* In delivery by *sliding* (*left*), the forceps are applied transversely in the pre-equatorial zone, the iris being simultaneously pushed aside. In *tumbling* (*right*), the forceps are passed closed beneath the iris to the pre-equatorial zone on the opposite side and then opened. The expressor then raises the vitreous pressure until the lens is pressed against the forceps and sufficient frictional resistance is created between the capsule and jaws. Then the forceps blades are closed. A solid grip on the capsule is confirmed by tactile feedback, i.e., by noting the transmission of diaphragm tension to the forceps: The resistance to slight lateral movements of the forceps changes as the vitreous pressure is raised by the expressor.

b, c *Tumbling technique.*
b *Formation of initial gap.* Traction on the forceps is directed straight toward the pupil center to make the zonule tense. If this traction is precisely *horizontal*, the initial phase of the reversing maneuver has begun (*diagram at right*). The expressor, applied as a zonulotome, simultaneously forms and tamponades the initial gap.

c *Delivery of lens through pupil and incision.* The vitreous pressure is increased to initiate locomotion. The zonule is made tense by zig-zag movements of gradually increasing amplitude (see Fig. 8.3c). Countermovements are made with the expressor to rupture the zonule (parallel to the vitreous face, see Fig. 8.4c, B). Following separation of the zonule inferiorly, the forceps are passed toward the corneal opening for the second phase of the reversing maneuver (*diagram at right*). The expressor is applied with its broadest surface to break the lateral zonule and simultaneously tamponade the enlarging zonular gap.

d *Final phase.* All pressure is released as soon as the largest lens cross-section has passed through the corneal opening. The lens is wheeled out over one edge of the incision. The incision is tamponaded with the expressor

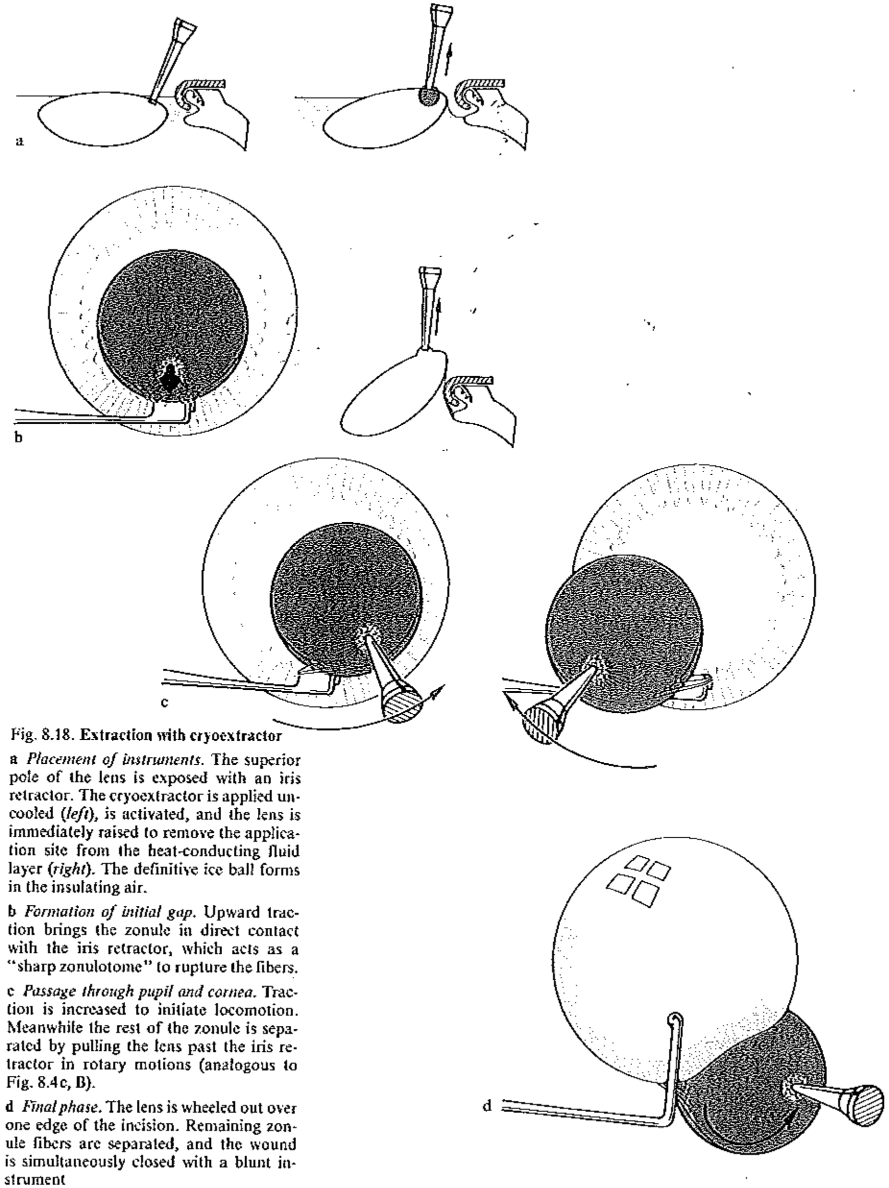


Fig. 8.18. Extraction with cryoextractor

a *Placement of instruments.* The superior pole of the lens is exposed with an iris retractor. The cryoextractor is applied uncooled (*left*), is activated, and the lens is immediately raised to remove the application site from the heat-conducting fluid layer (*right*). The definitive ice ball forms in the insulating air.

b *Formation of initial gap.* Upward traction brings the zonule in direct contact with the iris retractor, which acts as a "sharp zonulotome" to rupture the fibers.

c *Passage through pupil and cornea.* Traction is increased to initiate locomotion. Meanwhile the rest of the zonule is separated by pulling the lens past the iris retractor in rotary motions (analogous to Fig. 8.4c, B).

d *Final phase.* The lens is wheeled out over one edge of the incision. Remaining zonule fibers are separated, and the wound is simultaneously closed with a blunt instrument

The precise coordination of forces is easier if the lens can respond to the forces freely. This is facilitated by using a grasping instrument that has a *small contact area.*[14]

In delivery by *tumbling*, only one zonule gap is created and is easily tamponaded; this facilitates expression maneuvers. Delivery by *sliding* involves the creation of multiple gaps, which are difficult to tamponade; this situation favors delivery predominantly by traction.

Combined extraction and expression (Fig. 8.17) is in principle a controlled expression in which pressure serves as the primary motor while traction is used mainly for control.

Extraction

When delivery is effected purely by extraction (Fig. 8.18), all applied forces are exerted on the lens capsule. Hence, the main problem in this technique is to *relieve tension on the capsule* to avoid capsule rupture.

One way to accomplish this is to use an extractor that establishes a *large contact area* with the lens (possibly including the contents of the capsule; see Table 8.1). Another way is to *reduce the force applied in separating the zonule* (enzyme zonulolysis, mechanical zonulotomy). If, despite such measures, there is evidence of impending capsule rupture (traction folds), the direction of the traction is altered in an effort to relieve stress on the capsule by selective fiber tension.

The advantage of delivery by extraction alone is that no pressure is exerted on the vitreous chamber – an important safeguard against undesired vitreous prolapse.

8.2.6 Completing the Intracapsular Delivery after Inadvertent Capsule Rupture

If the capsule ruptures accidentally during a planned intracapsular extraction, the surgeon may elect to leave the capsule in the eye (converting to an *extracapsular extraction*), or he may pursue the original plan of a *complete lens removal.*

The *capsule is grasped* by identifying its *free edges* and bringing them between the forceps jaws (Fig. 8.19). If the capsule is ruptured at the **start of the delivery** (Fig. 8.20), the lesion lies at the application site of the grasping instrument. Tags of capsule are recognized by their motion during irrigation of the anterior chamber. If the zonule is still intact, the procedure can be converted to an extracapsular extraction.

If the capsule ruptures in the **final phase** of the delivery (Fig. 8.21), capsule remnants are accessible at the lip of the incision. By that point the zonule is partially separated and offers little resistance; conversion to an extracapsular delivery is no longer possible.

During *extraction of the capsule*, forces are no longer transmitted to the zonule as a whole since the capsular bag is destroyed (see p. 221). Thus, the zonular fibers can be made tense only by applying the forceps *close to their insertion.* Since the distance between the forceps and remaining intact fibers increases as the extraction proceeds, the forceps must be continually reapplied closer to the fibers to be divided (*taking alternate grips with two pairs of forceps*). The applied forces are optimally utilized by employing selective fiber tension (Fig. 8.22).

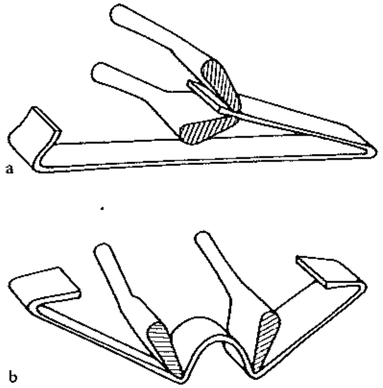


Fig. 8.19. Grasping the torn capsule (here: With capsule forceps)

a The free edge of the capsule is grasped at the rupture site. *Note:* The forceps is held horizontally, i.e., parallel to the capsular plane.

b If the forceps were applied vertically, as for grasping an intact lens (see Fig. 8.13), it could grasp only by making a fold. But this could cause rupture of the posterior capsule or incarceration of vitreous

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[14] The associated danger of capsule rupture is reduced by switching to expression when warning signs appear (folds in the lens capsule).

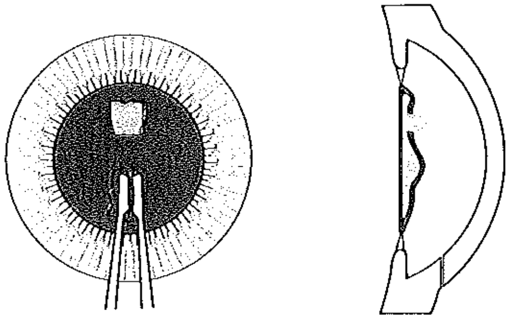


Fig. 8.20. Rupture of the capsule on grasping the lens. The rupture occurs at the site where the extractor (here: Forceps) is applied. The capsule remains tense because the zonule is still intact

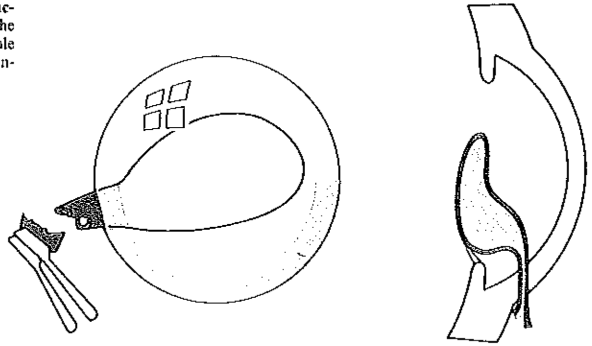


Fig. 8.21. Rupture of the capsule on extraction. If the capsule ruptures during the course of extraction, part of the capsule is already within the incision, and the zonule is partially divided

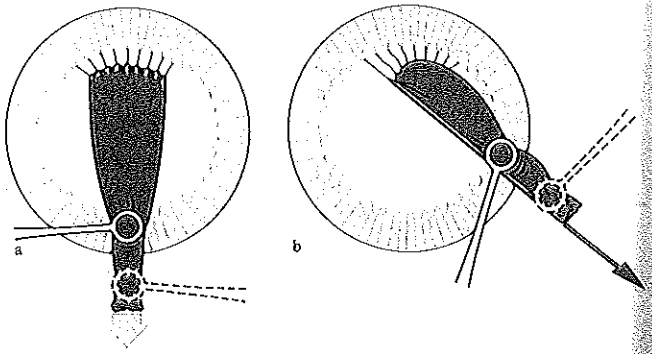


Fig. 8.22. Extraction of the capsule (here: With ring forceps)

a If the pull on the capsule is centripetal (i.e., in line with the normal course of the zonule fibers), a diffuse tension is exerted. The tension on each fiber is low compared with the force applied.

b Selective tension (i.e., traction applied at a large angle to the anatomic course of the fibers, see Fig. 2.55) exerts maximum tension on the fibers that are to be separated next, while all others fibers remain lax.
Note: The capsule is extracted by taking alternate grips with two forceps in a "hand-over-hand" fashion

8.3 Extracapsular Cataract Operation

The goal of the extracapsular cataract operation is to remove the contents of the lens bag while preserving the *integrity of the zonulocapsular membrane*. While the intracapsular delivery aims at avoiding the destruction of the anterior hyaloid, all measures in the extracapsular delivery are geared toward preventing lesions of the zonule and the posterior lens capsule.

Each step of the procedure weakens the *diaphragm* separating the anterior chamber from the vitreous chamber, as first the nucleus and then the cortex of the lens are removed, finally leaving only the posterior capsule behind (see Fig. 8.1c). The ability of the open capsular bag to retain its shape depends increasingly on the pressure differential between the bag and its surroundings. A high *intralenticular pressure* can develop if the outflow resistance from the capsular bag is higher than the outflow resistance from the adjacent ocular chamber.

From the standpoint of spatial tactics, we can distinguish between procedures in which the capsule retains its quality as a *separate pressure chamber* and procedures in which the capsule simply forms part of the wall of the anterior chamber or vitreous chamber (Fig. 8.23). This distinction is based on the size of the opening in the lens capsule.

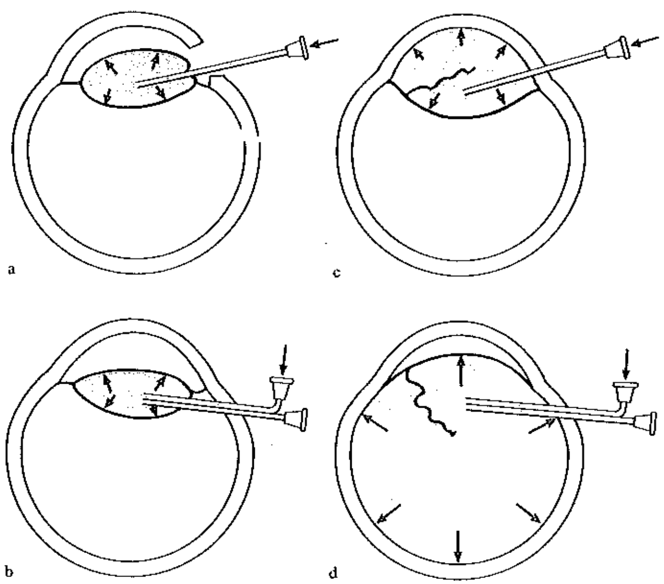


Fig. 8.23. Space-tactical aspects of extracapsular cataract extraction

a, b Capsular bag as a separate pressure chamber.
c, d Capsular bag communicating with the adjacent pressure chambers.
a, c Approach through the anterior chamber.
b, d Approach through the vitreous.

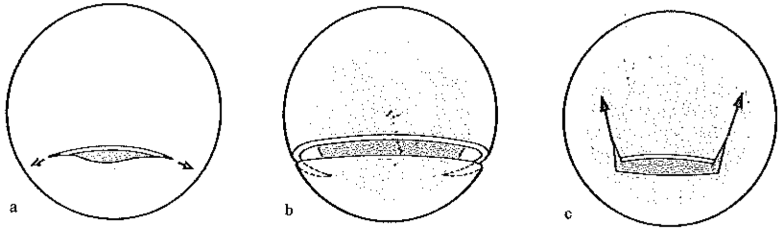
a Capsular pressure chamber with approach through the anterior chamber: The outflow resistance from the capsular bag is higher than the outflow resistance from the anterior chamber. Thus the pressure within the capsule can rise higher than the ambient pressure; the bag can be inflated and will retain its shape (space-tactical condition for endocapsular techniques).

b Capsular pressure chamber with approach through the vitreous (e.g. for lensectomy: The opening in the ocular wall (pars plana) is tamponaded to prevent vitreous prolapse. Thus, the opening in the capsular bag also must be tight if intracapsular pressure is to develop relative to adjacent chambers.

c Capsular bag as part of the anterior chamber: If the outflow resistance from the capsular bag is lower than that from the anterior chamber, the pressures in both chambers will be equal (space-tactical condition for "open capsule" techniques).

d Capsular bag as part of the vitreous chamber: If the opening in the capsule is not watertight, the bag will behave as part of the vitreous pressure system

8.24



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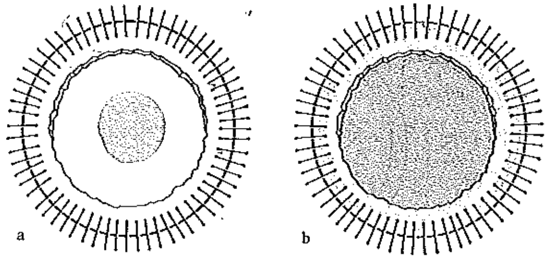

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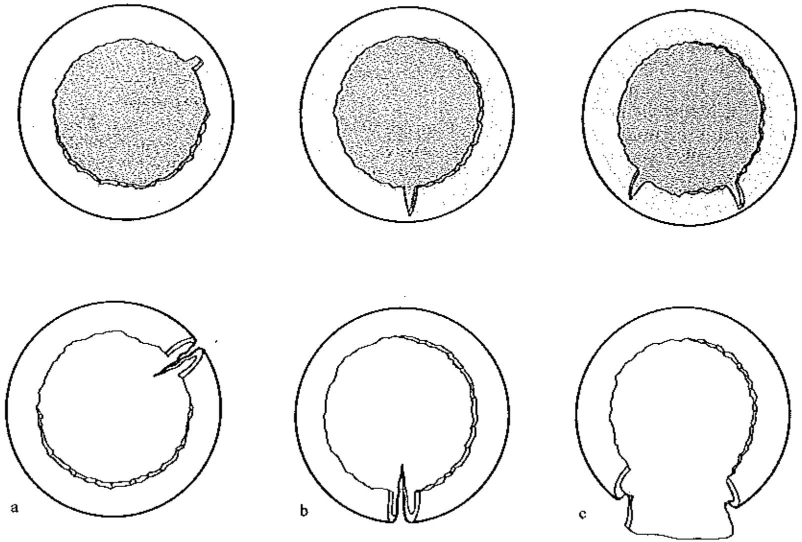

Fig. 8.24. Slitlike anterior capsulotomies

a A slitlike opening in the anterior capsule maintains a relatively high outflow resistance from the capsular bag. Capsulotomies of this kind are suitable for endocapsular deliveries provided the opening can accommodate the nucleus (*gray*).

b If the nucleus is too large, the capsulotomy will tear as the nucleus passes through. The tear extends in the original direction of the capsulotomy, spreading into the zonule or even the posterior capsule.

c With a large nucleus, the tear can be redirected from the lens equator (*arrows*) by preplacing small, angled extensions at the ends of the capsulotomy

Fig. 8.25. Circular anterior capsulectomy

a The opening in the anterior capsule should spare the zonule attachments to preserve the integrity of the zonulocapsular diaphragm ("maximum allowable opening").

b If the nucleus is too large to fit through an opening of maximum allowable size ("insufficient maximum opening"), it cannot be delivered without endangering the zonulocapsular diaphragm

Fig. 8.26. Circular capsulectomy: Relaxing incisions to enlarge an "insufficient maximum opening". *Above:* Appearance of the anterior capsulectomy before delivery of a too-large nucleus; *below:* After delivery of the nucleus.

a Tearing at incidental notches in the margin of the capsulectomy. The deepest notch is the weakest point, and the capsule will tear there when the nucleus is delivered. The random location of this site means that it may be tactically unfavorable.

b Planned relaxing incision at a favorable location (near the entry site into the anterior chamber). The direction of tear expansion is confined to an area easily monitored from the access site by deliberately placing a radial incision there extending from the circular capsulectomy.

c Dual relaxing incisions create a trapdoor-like opening in the border of the anterior capsule. Because the expansion is provided by two incisions instead of one, each of the incisions will undergo less additional tearing during the delivery than a single incision as in **b**

8.3.1 Anterior Capsulotomy

The size and shape of the anterior capsulotomy are planned with the dual objectives of removing the lens contents *and* preserving the integrity of the zonulocapsular diaphragm. Thus, the *maximum size of the capsulotomy* opening is limited by the area of attachment of the zonular fibers on the capsule (Fig. 8.25), while its *minimum size* depends on the size of the noncompliant lens matter that must traverse the opening, i.e., on the size of the lens nucleus. If the nucleus is so large that it would require a minimum capsulotomy larger than the opening permitted by the zonule attachments, the emerging nucleus might cause the capsule to rupture into areas that should remain intact. Thus, the *shape of the capsulotomy* must be such that any further tears accompanying extraction of the nucleus will occur in directions that do not jeopardize the zonule or posterior capsule (Figs. 8.24, 8.26).

In terms of surgical technique, the lens capsule behaves as a *compliant, resilient membrane.* This means that when the tissue is cut with a sharp blade, it manifests the classic forward and lateral shifting tendencies described earlier. When the tissue is divided bluntly (by *tearing*), the shape and direction of the tear depend entirely on the forces applied, since the capsule is structurally homogeneous and contains no anatomic "paths of least resistance."

Cutting the Lens Capsule

In a sharp capsulotomy the blade must first penetrate the lens capsule. Thereafter only the *blade* is moved; the *capsule* should remain stationary to ensure that no forces are transmitted to the zonule.

The *starting point of the incision* is defined by the point of application of the blade. At that site the blade is inserted to the proper depth.[15] Thereafter the section theoretically proceeds in the guidance direction of the blade, although the actual result is influenced by the forward and lateral shifting tendencies of the capsular tissue.

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[15] If applied too superficially, the blade will tear the capsule rather than divide it. In this case the starting point of the capsule lesion does not coincide with the point of blade application. If inserted too deeply, the blade will snag the lens contents and, when moved, will cause motion of the nucleus and cortex. Thus, proper blade depth is checked by watching for concomitant movements: In cutting neither the capsule nor lens contents should move with the blade.

The *forward shifting tendency* causes the incision to become shorter than the path traveled by the blade (Fig. 8.27). Thus, while the starting point of the incision is plainly defined, its end point is not. If precision requires that the incision reach a specific point, this can be done only by starting the cut at that point or by reapplying the blade there.

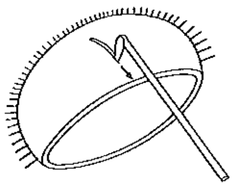
The *lateral shifting tendency* is a factor whenever the guidance path of the blade does not coincide with its preferential path (see Fig. 2.60). Such discrepancies are scarcely avoidable when the blade is introduced through a narrow limbal access opening (Fig. 8.28).

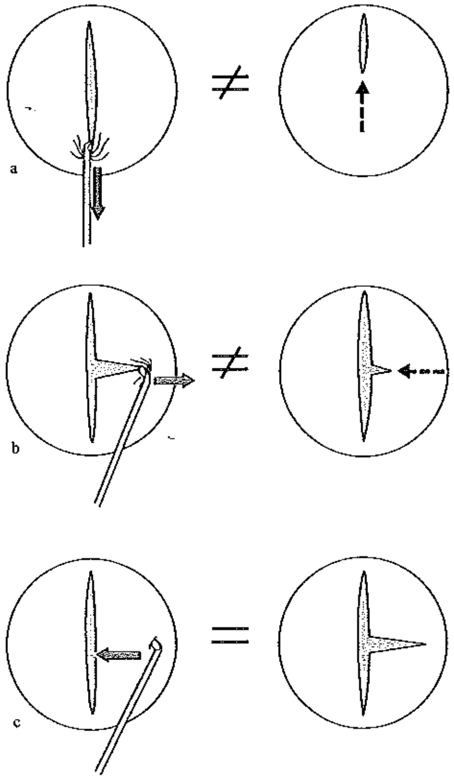
Both shifting tendencies depend on the sectility of the capsule. Because the capsular tension dwindles as the cut proceeds, both tendencies increase with the length of the incision. If the capsule becomes so lax that it can no longer be cut with a blade, the capsulotomy is completed with a scissors or by tearing.

Tearing the Lens Capsule

In this method the function of the capsulotomy instrument is to *grasp* rather than divide the tissue. The division is accomplished by subjecting the capsule to excessive tension. This is the basic feature that distinguishes capsulotomies performed by tearing as opposed to cutting: the cystitome acts as a *blunt instrument* and is *connected* to the capsule in such a way that motion of the instrument elicits *motion of the capsule*.

The main problem in tearing is control. Given the absence of predefined rupture lines in the capsule, the cleavage process is influenced by the relative tensions that develop, and these can change constantly as the capsulotomy proceeds. Even the site of the *initial tear* cannot be predicted with accuracy; it occurs





8.27

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Fig. 8.27. Capsulotomy by cutting: Effect of forward shifting tendency on length of cut. *Left*: Motion of the cutting edge; *right*: Result.

a Effect of forward shifting tendency on a straight incision: The resulting cut is shorter than the path traveled by the cutting edge.

b Effect of forward shifting tendency on a lateral extension of the capsulotomy: The lateral extension is considerably shorter than the path traveled by the cutting edge, because the primary incision had made the capsule more lax than in a. If the capsule is so lax that it cannot be cut at all, the ends of the primary incision will tear toward the periphery (analogous to Fig. 8.28c).

c Forward shifting is avoided by initiating the extension away from the primary capsulotomy, in tissue that is more tense, and carrying it toward the main incision. The length of the cut then equals the path traveled by the cutting edge

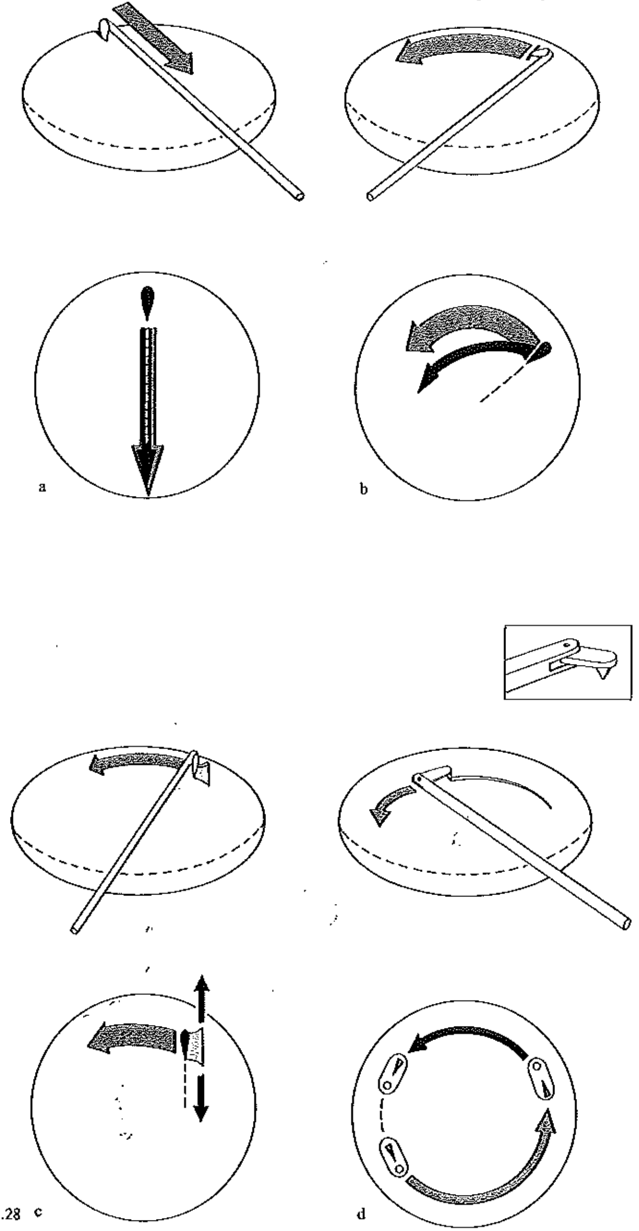
Fig. 8.28. Capsulotomy by cutting: Effect of lateral shifting tendency on direction of cut. (Illustrated for a discission knife.) *Red arrow*: Guidance path; *hatched line*: Preferential path; *black arrow*: Direction of resulting cut.

a Cutting the capsule with a straight pulling motion: The incision starts at the point where the blade is applied. The guidance path is congruent with the preferential path, so the direction of the incision follows the path of the cutting edge.

b Lateral sweep with the blade angled: If the knife is swept laterally, the guidance path forms an angle with the preferential path. The asymmetric resistances produce a lateral shifting tendency, and the capsulotomy deviates in the direction of the corneal incision.

c Lateral sweep with the blade upright: In this maneuver the blade behaves as a blunt instrument, so the capsulotomy is made by tearing rather than cutting. The capsule will tear into the zonule at right angles to the direction of blade motion.

d Circular incision made by constantly realigning the preferential path with the guidance path: The stem must rotate through 360° in order to make a circular incision. Given the limited space available, this is possible only if the stem is very short. The capsulotome pictured here (*inset*) has an extremely short stem connected to the handle by a swivel joint. The stem can rotate through a full circle even when the handle has been inserted through a small opening



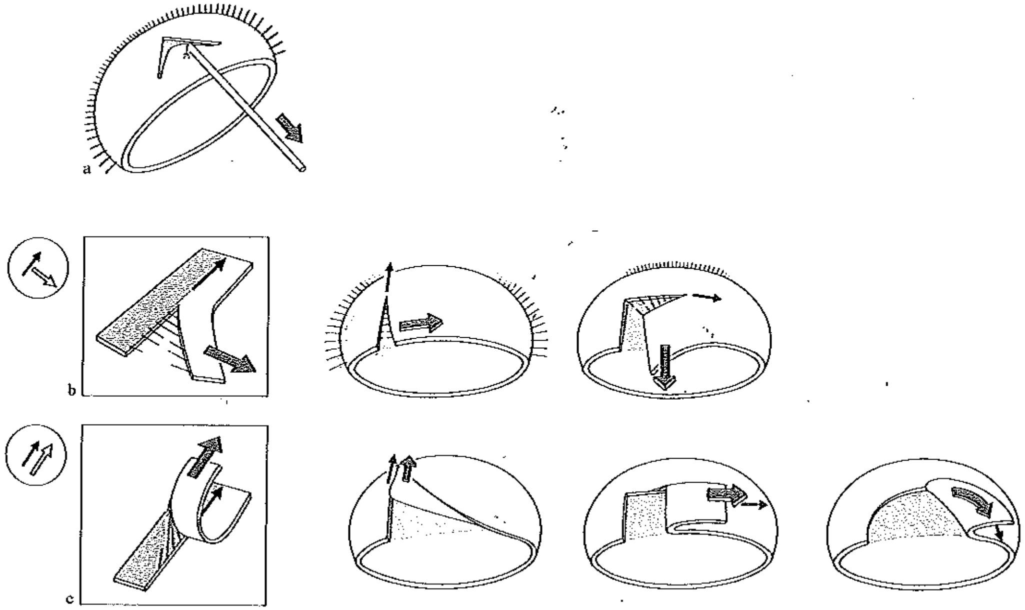


Fig. 8.29. Capsulotomy by tearing

a Initial tear. The cystotome is pressed against the capsule, this working motion serving to produce a high frictional resistance between the instrument and capsule (=grasping). Pulling the cystotome (guidance motion) increases the tension of the capsule until it gives way. This tension is transmitted to the zonule; if that is the area of least resistance, the zonule will tear instead of the capsule.
Note: Because the tear can initiate anywhere between the attachment of the zonule and the site of instrument contact, the instrument should be applied farther away from the zonule for tearing than for cutting.

b When tension (*red arrow*) is applied parallel to the capsule surface, the tear will extend (*black arrow*) at right angles to the direction of pull (*inset*). Thus, a tear running parallel to the lens border (*left*) will not turn centripetally when tension is directed toward the center of the capsule, but will extend laterally toward the zonule. The tear is redirected (*right*) by pulling the capsule parallel to the border of the initial tear (i.e., at right angles to the new direction in which the tear is to extend).

c If the capsule is reflected as it is torn free (*inset*), the tear will proceed in the direction in which the reflected flap is pulled (*left*). With this technique it is easier to control abrupt direction changes (*center*), and it is possible to produce a circular capsulectomy (*right*)

somewhere between the point of application of the instrument and the line of attachment of the zonule (Fig. 8.29a).[16] The *direction of extension* of the tear is also difficult to predict, for it does not follow the guidance motions of the instrument. The fibers rupture in the direction of the highest tension, so the tear extends at right angles to the direction in which the capsular tissue is pulled (Fig. 8.29b). Once a tear starts to extend in a particular direction, it tends to maintain that course.[17] When a tear must be abruptly redirected, the best precision is achieved by reflecting the mobilized part of the capsule as the tear proceeds (Fig. 8.29c).

Thus, it is not possible to control precisely the starting point, end point, or direction of the "blunt" capsulotomy (Figs. 8.30 and 8.31). None of these quantities correlate closely with the position or motion of the capsulotomy instrument, so none can be estimated from the behavior of the instrument.[18] Close

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[16] The site of the initial tear depends in part on the speed of the tearing motion. The faster the instrument is pulled back, the greater the likelihood that the tear will initiate close to the point where the instrument is applied.

[17] Enlargement of a tear in the initial direction must be anticipated when the capsular tension is diffusely increased, as during delivery of the nucleus or a sudden elevation of the vitreous pressure (see Figs. 8.24 and 8.26).

[18] It is especially dangerous to attempt to grasp and tear off tags of capsule with an aspirating cannula. Neither the direction nor the force of the traction can be controlled, for the traction is produced not just by guidance motions (which can be controlled by the operator) but also by the suction in the cannula.

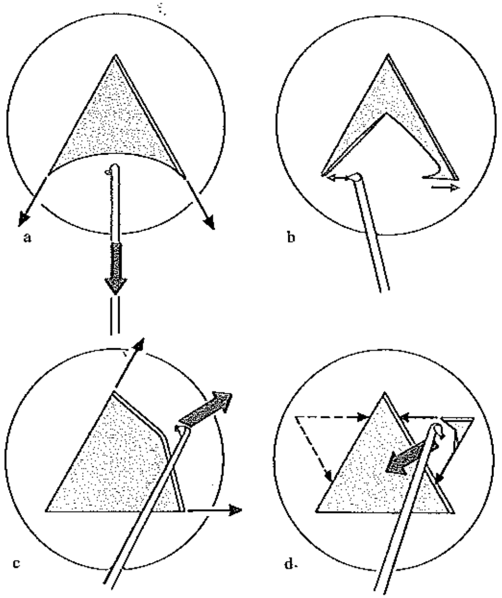

Fig. 8.30. Triangular capsulectomy by tearing

a Pulling the cystotome back from the initial gap creates a tear extending in two directions (see Fig. 8.29a), and a triangular defect is formed. With continued traction, there is a great danger of extension into the zonule (*arrows*).

b This is avoided by redirecting the tears at the proper point. As this is difficult to accomplish by tearing alone, it is safer to cut the corners of the triangle with a scissors or a small, sharp knife (a knife is moved toward the preexisting tear as shown in Fig. 8.27c). With the corners thus redirected, the triangular flap can be pulled toward the center of the pupil.

c To enlarge a triangular capsulectomy, it is not advisable to tear from the existing opening toward the periphery, as this would risk extension of the tears into the zonule.

d Instead the cystotome is reapplied outside the capsulectomy and pulled centripetally toward the existing capsular defect

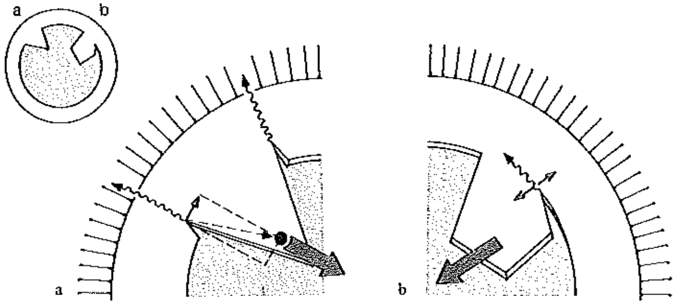

Fig. 8.31. Removal of capsule tags by tearing

a If the small tears flanking the tag are both oriented radially, traction in any direction, even centripetally (*inset*), has components that would extend the tears toward the lens equator. Triangular tags of this kind are better not be removed by tearing.[19]

b If the end of the tear at the flap is angled parallel to the lens equator, the tag is easily removed by centripetal traction (see Fig. 8.29b)

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[19] A sudden tug toward the center of the lens would offer the best chance of success but is dangerous in this situation because of the peripheral location of the tag. A sudden tug with forceps, if not successful at first attempt, would tear the capsule into the zonule.

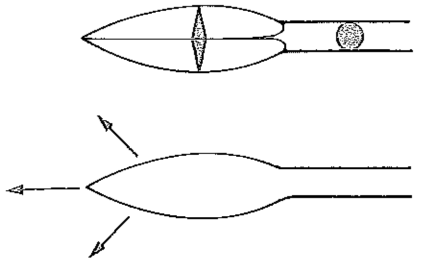

Fig. 8.32. Straight discission knife. Straight discission knives behave as sharp instruments when moved forward as well as laterally. They do not divide tissues when pulled backward (*below*). *Note*: If the cross-sections of the blade and stem (*gray*) are of equal surface, the knife is suitable for use in a no-flow system, since it can be advanced and withdrawn without causing aqueous loss. (see Fig. 2.4b)

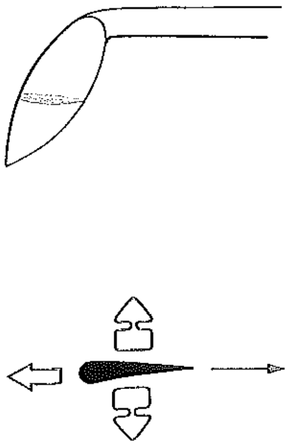

Fig. 8.33. Angled discission knives. Angulated discission knives behave as sharp instruments only when pulled backward, as the cross-section of the blade indicates (*below*). They are blunt when moved forward or laterally

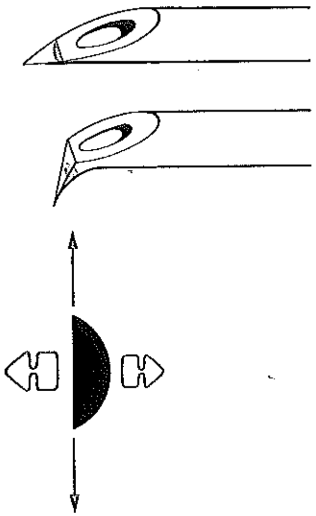

Fig. 8.34. Injection cannula as a cystotome. A cannula bent sharply at the tip makes an excellent cystotome. A cross-section through the tip (*below*) shows that it behaves as a sharp instrument when moved laterally and as a blunt instrument when advanced or withdrawn

visual monitoring, then, is essential when tearing is employed.[20] The surgeon should not only focus his attention on the tear and its extension but should also observe the rim of capsule that is left adjacent to the zonule. Motion of this area signifies an interference with the cleavage process which, if neglected, may cause damage to the zonule.

Methods of Capsulotomy

The difficulties of controlling a capsulotomy performed by cutting or tearing are compounded by the fact that it is often difficult to predict whether the capsulotomy instrument will cut or tear the capsule in a given situation.

One factor is the *instrument design*. Any blade will exert a sharp, cutting action only in certain directions while producing a blunt, tearing action in all other directions (Figs. 8.32–8.34).

Another factor is the loss of sectility that occurs with *diminishing capsular tension*. It is important, therefore, to maintain a high capsule tension for as long as possible. On the one hand, this means maintaining the tension of the diaphragm as a whole and preventing a general fall of intraocular pressure by using the capsulotomy instruments in a no-outflow system (Figs. 8.35, 8.36b) or a controlled outflow system (Fig. 8.36c). On the other hand following the initial incision, capsule tension is maintained by preventing the premature discharge of lens matter. This is achieved by occluding the capsulotomy opening with air or viscoelastic material (Fig. 8.37). Despite these measures, the capsule will still tend to become increasingly lax and less sectile as the capsulotomy proceeds. That is why a perfect circular excision is difficult to achieve even

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[20] Note: Optical phenomena in the underlying cortex may interfere with visual monitoring of the capsule. They are much more conspicuous under coaxial illumination than the subtle changes in the thin, transparent capsule and may hamper recognition of the capsular border. The latter is most easily identified by injecting air into the anterior chamber, as this brings out reflexes that help define the slightest irregularities on the lens surface.

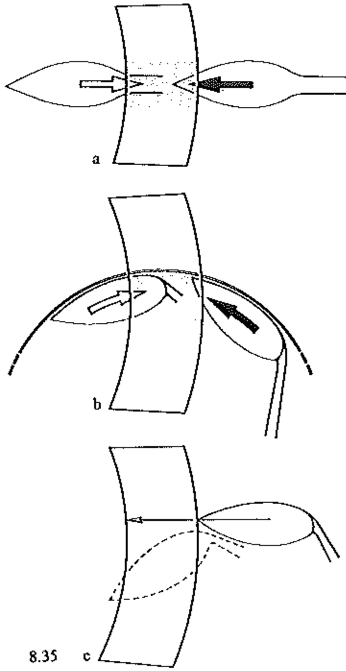

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Fig. 8.35. Insertion of discission knives in a no-flow system. Instruments used in a no-flow system must be inserted so that the cross-section of the opening in the anterior chamber precisely matches the cross-section of the instrument shaft. It is not sufficient for the blade to have the appropriate dimensions (see diagram in Fig. 8.32, *top*); additionally the blade must be guided so that it does not enlarge the opening.

a Discission knives with two cutting edges are advanced precisely along their axis.

b Discission knives with one cutting edge are guided along the blunt back of the blade, so they are inserted on a curved path. Note the different angle of application (compared with **a**): The point is directed obliquely toward the back of the blade.

c If the blade were inserted in line with its own axis, it would be deflected by its blunt back (*dashed line*). Any countermaneuvers intended to keep the knife on the desired path (*arrow*) would produce a high resistance and deform the wound area

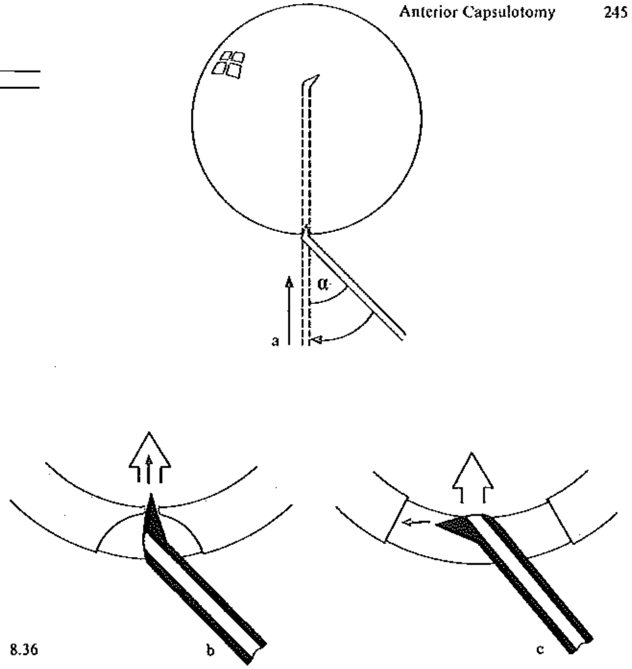

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Fig. 8.36. Inserting an injection cannula with an angled tip

a The cannula is applied obliquely for insertion and is not straightened until the tip is inside the anterior chamber.

b Insertion in a no-flow system. The tip cuts its own path, so it must behave as a sharp instrument. The tip is applied perpendicularly and is thrust into the chamber. Thus, the obliquity of the stem on insertion (i.e., the angle α between the stem and a perpendicular to the tissue surface) is determined by the degree of angulation of the tip. *Note*: To reduce the resistance on insertion a preliminary partial thickness incision may be prepared.

c For insertion through a wide incision, the cannula is held in a "blunt" position: The blunt face is leading, and the tip points away from the chamber. The orifice is directed toward the anterior chamber so that fluid can be infused through the cannula immediately after entry.

Large arrow: Guidance direction of cannula.

Small arrow: Direction of tip (=preferential path)

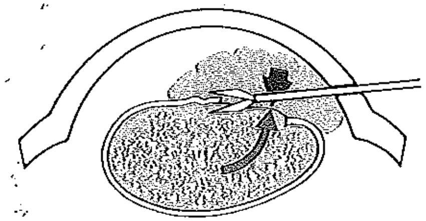

Fig. 8.37. Preservation of capsule tension by using viscoblockade to maintain pressure in the capsular bag. Viscoelastic material is placed over the capsulotomy to keep the liquefied lens contents from escaping. This maintains the sectility of the capsule and facilitates visual monitoring for continuing the capsulotomy

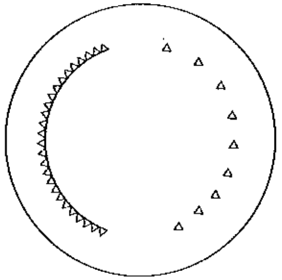

Fig. 8.38. **Performing the capsulotomy in mini-steps.** Multiple, separate capsulotomies of minimal length eliminate the problems associated with a long travel path of discission instruments. The excision can be made circular or any shape desired using the mini-step technique. The perforations can be placed so close together that a continuous capsulotomy is obtained (*left*). Alternatively, intact tissue bridges may initially be left between the perforations so that capsule tension is maintained along the whole circumference (*right*)

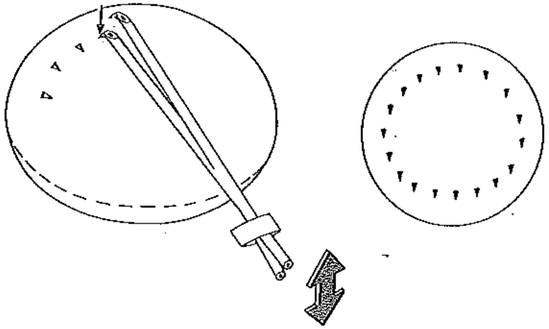

Fig. 8.39. **Mini-step capsulotomy with an up-and-down action of an angled cannula tip.** The cannula cystitome is bent as shown in Fig. 8.34. The amplitude of the downstroke is necessarily small due to space limitations. Whether this is adequate to perforate the capsule depends on "sharpness," i.e., on the cutting ability of the instrument and the sectility of the capsule (capsular tension). The resistance to perforation of the capsule also depends on the condition of the cortex. If the surgeon attempts to compensate for poor sharpness by increasing the amplitude of the up-and-down motion, tension will be exerted on the zonule

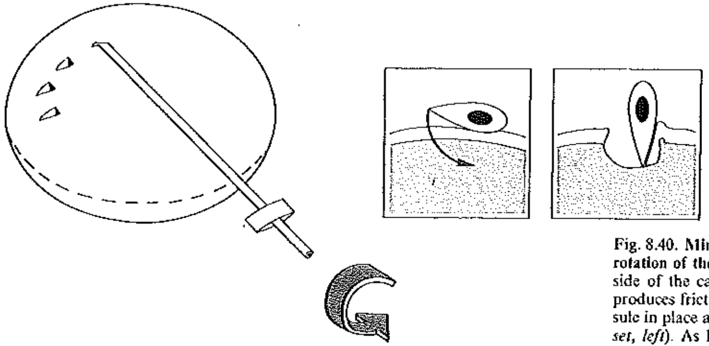

Fig. 8.40. **Mini-step capsulotomy by axial rotation of the cannula.** Placing the blunt side of the cannula tip onto the capsule produces friction that helps hold the capsule in place and improves its sectility (*inset, left*). As long as just the pointed tip of the cannula penetrates the capsule, a cutting effect is achieved. But if the cannula is rotated further, the capsule is acted upon by the blunter sides of the bent tip, and a tearing action may result (*inset, right*)

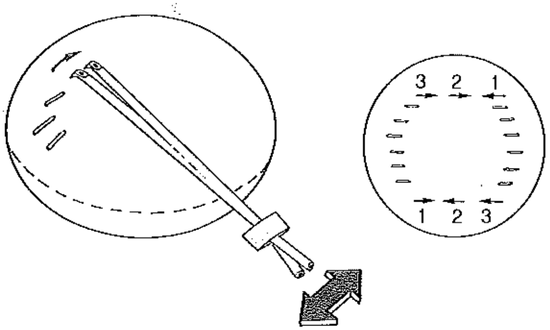

Fig. 8.41. **Mini-step capsulotomy with a lateral sweeping motion of the cannula tip.** The tip behaves as a sharp instrument when moved laterally, so small incisions are produced. Cutting *toward* the center of the capsule (*1, 3*) places stress on the zonule, but if the zonule is sufficiently resistant, tension adequate for the capsulotomy exists around the whole circumference of the lens. Cutting *away from* the center of the capsule (*2*) relieves stress on the zonule, but the tension for the cutting action dwindles as the capsulotomy proceeds. This places greater demands on the cutting ability of the instrument.
Note: Long incisions usually cannot be made because of diminishing capsule tension. That is why multiple small incisions are preferred even along the upper and lower circumference of the capsulotomy, where theoretically longer incisions could be made. Note the sequence of the mini-cuts in the diagram on the right!

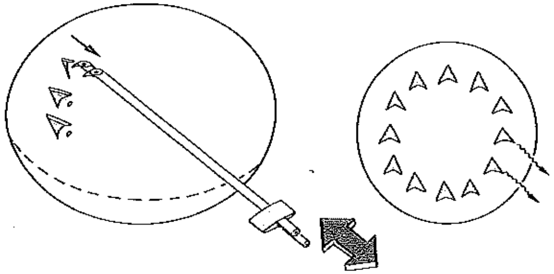

Fig. 8.42. **Mini-step capsulotomy with forward and backward motions of the cannula.** The cannula tip behaves as a blunt instrument, producing triangular perforations.
Note: In the lateral perforations, there is a danger of tearing into the zonule (*arrows* in the diagram on the right)

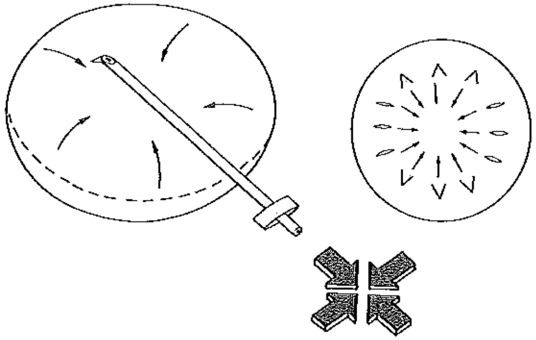

Fig. 8.43. **Mini-step capsulotomy with radial perforations of the capsule.** When radial guidance motions are used, the cannula cuts the lateral portions of the capsule while tearing the upper and lower portions

when an extremely sharp cystotome is used.

Since the difficulties of the procedure correlate with the length of the capsulotomy, they can be reduced by subdividing the procedure into **multiple mini-steps.** The smaller each individual step, the less it matters whether the tissue is cut or torn (Fig. 8.38). The "mini-step" capsulotomy can solve the problem of diminishing capsule tension by leaving intact tissue bridges between the perforations that outline the piece of capsule to be removed. The individual cuts are then joined together by a tearing procedure in a second step. Mini-step capsulotomies are illustrated in Figs. 8.39–8.43.

Low sectility can be compensated for by using fast, jabbing motions of the cystitome. Control problems are managed by keeping the amplitude of the motions very small. This

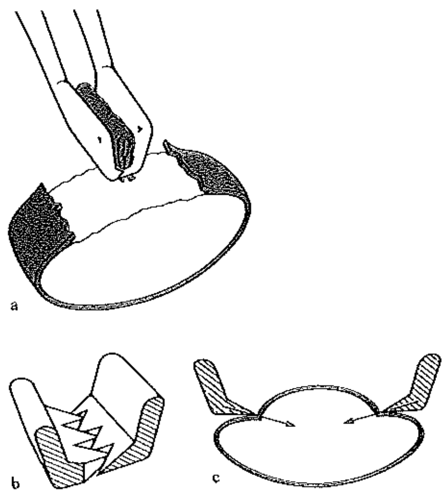

Fig. 8.44. **Anterior capsulectomy with forceps**

a The forceps jaws tear out the tissue that is gripped between them.

b When closed, the jaws are smooth externally and can be moved about safely within the anterior chamber.

c For grasping, the sharp teeth are pressed into the lens so that their preferential paths (*arrows*) are nearly perpendicular to the capsule surface

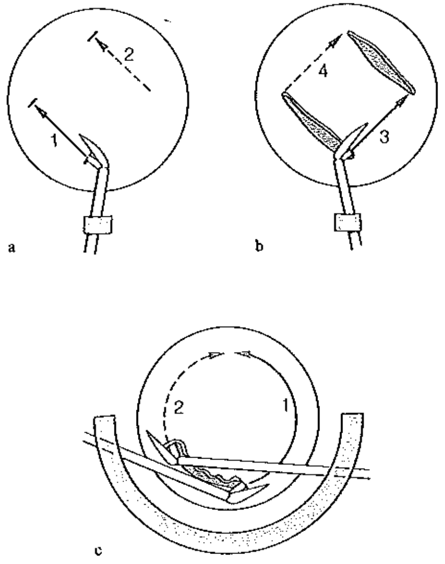

Fig. 8.45. **Anterior capsulectomy with microscissors**

a, b When introduced through a small access opening, one microscissors with a 45° angulation can make a diamond-shaped capsulectomy. Two parallel incisions are made with the scissors held one way (**a**), then the instrument is turned over to make the two remaining incisions (**b**).

c When greater access is available, a circular capsulectomy can be made by cutting half the circle (*solid line*), turning the scissors over, and cutting the remaining half (*broken line*)

can be done, for example, by rotating the cystitome about its own axis (Fig. 8.40). A more technically elaborate solution is the ultrasound cystitome.

Toothed capsule forceps automatically tense the capsule upon closure (Fig. 8.44). Control is difficult, however, because the area of jaw contact and thus the pressure on the capsule are difficult to define. Therefore one cannot predict whether the forceps will exert a cutting or tearing action in a given situation, and whether the capsule or the zonule is more likely to give way.

A very precise instrument for capsulotomies is the **microscissors** (Fig. 8.45). Because each blade meets an opposing surface, scissors can always cut without tearing, regardless of the capsule tension. Microscissors are especially indicated when tearing must be avoided, e.g., when the resistance of the zonule is presumed to be low[21] or an abrupt change of direction is required.[22]

8.3.2 Delivery of the Nucleus

The maneuvers for delivering the nucleus, like those for removing the entire lens, consist of *mobilization* (nucleolysis), *alignment*, and *locomotion*. However, many more technical variations are possible in delivery of the nucleus due to the great variability in the size, compactness, and surface characteristics of the nucleus and the stress tolerance of the diaphragm. Basically the nucleus is more difficult to grasp than the intact lens, and its surface is rougher. On the one hand, this means that the *external resistances* (friction) are higher, so greater forces may be needed to effect the delivery; on the other, the *internal resistances* (compactness) are lower, so the direct application of forces to the nucleus is less efficient. Locally applied forces (e.g., hooks, forceps, or cryoprobes) act upon the whole nucleus only if its internal resistance to dissociation is greater than the external, frictional resistance to motion of the nucleus. This means that control of the delivery not only involves controlling the *force applied to the nucleus* but is especially concerned with *reducing frictional resistance* at the surface of the nucleus.[23]

Nucleolysis

The nucleus and cortex do not form discrete anatomic structures, and (in contrast to the zonule in the intracapsular delivery) there is no definite cleavage plane separating the part to be removed from structures that are to be left behind. The boundary, rather, lies somewhere in a zone of gradually increasing compactness, and the *location of the cleavage plane* for a given tissue structure will vary according to the nature of the applied forces (i.e., site of application, magnitude, direction, and velocity).

Delivery of the nucleus is influenced not only by the properties of the nucleus but also by the *properties of the cortex*. If motion of the nucleus exerts *pressure* on the cortex, the cortex will act as a cushion over the lens capsule. A thin or noncompliant cortex increases the danger of capsular damage when the nucleus is moved. A thick, compressible cortex enhances the safety of the nucleolysis, but all motions must be performed slowly enough to allow sufficient time for any compression or yielding of the cortex to occur.

If motion of the nucleus exerts *traction* on the cortex, remaining tissue attachments may transmit the forces to surrounding structures (capsule, zonule). The inherent dangers decrease as the nucleolysis proceeds. The surgeon confirms completion of the nucleolysis by noting that motion of the nucleus no longer elicits motion of the cortex or capsule.[24]

The *force* needed to mobilize the nucleus depends on the ease with which the attachments between the nucleus and cortex can be divided. This in turn depends on the difference in consistency between the part to be removed and the part that is to remain. If the consistency difference is large, applied forces will act locally at the plane of separation. But if the nucleus has a soft consistency similar to the cortex, the effects will be distributed evenly over a large tissue volume, and substantial force must be used to obtain a local separation (Fig. 8.46).

The *direction* of motion of the nucleus can be precisely controlled by the direct, **localized application** of forces. Using *lateral motions* to effect nucleolysis alters the volume distribution inside the capsular bag. Because some parts of the cortex are stretched and others are compressed, the amplitude of the lateral motion is limited by the compliance of the cortex (Fig. 8.47a). By contrast, *rotation* of the nucleus does not affect the cortical topography. An "infinite" excursion is possible.

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[21] After a prior vitrectomy or when there is risk of subluxation (e.g., in pseudoexfoliation syndrome or after trauma).

[22] Abrupt direction changes must be made when a tear threatens to spread into danger zones and a sharp-angle course correction is required. Examples are triangular flaps that tear into the zonule (see Fig. 8.30b) and partially divided tags of capsule (see Fig. 8.31b).

[23] E.g., by enlarging the capsulotomy, enlarging the pupil (see Figs. 7.36–7.38), extending the corneal incision, using glides to avoid entanglement with obstructions, or by reducing friction with viscoelastic lubricants.

[24] Thus, the safety of the nucleolysis is monitored by watching the capsule border. Any concomitant motion signifies possible force transfer to the zonule.

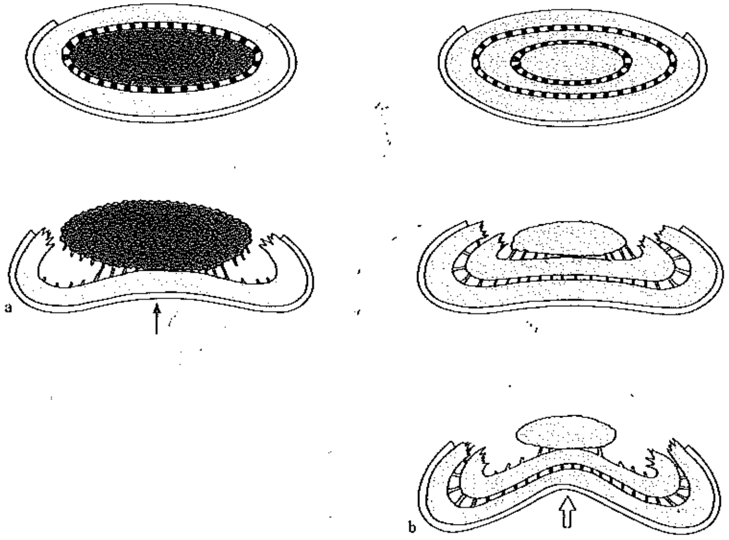

Fig. 8.46. **Nucleolysis by the indirect application of forces**

a Expression of a well-demarcated nucleus with a much harder consistency than the cortex (*top*). If the posterior capsule is driven forward and deformed by a rise of pressure in the vitreous, it will produce a similar deformation of the cortex. The hard nucleus is not deformed, however, and the geometric discrepancy between the nucleus and cortex leads to rupture of the connections (*bottom*).

b Expression of a soft nucleus having a consistency similar to that of the cortex (*top*). The nucleus also deforms in response to deformation of the cortex. As a result, tension on the connections is spread over multiple layers, and the tension in any one layer is insufficient to effect fiber rupture (*center*). The deformation must be markedly increased (i.e., the vitreous pressure must be further increased) to produce the critical tension necessary for rupture of the connections (*bottom*)

The resistance to the rotation is very high, however, because all the attachments are stretched simultaneously. The resulting danger of force transfer to the zonule can be reduced by starting the rotating maneuver at a small amplitude and gradually increasing the amplitude as the nucleus becomes loose (Fig. 8.47).

When forces are **applied diffusely**, the nucleus is mobilized by *pressure*. The pressure may be produced ambiently in the vitreous chamber (nucleolysis by expression), or the pressure within the capsular bag alone may be increased by injecting fluid between the nucleus and cortex (nucleolysis by *hydrodissection*).

Nucleolysis by expression is always combined with *locomotion*. The cortex is simultaneously loosened, facilitating subsequent corticolysis. The maneuver always affects a large ambient tissue volume due to the general pressure rise in the vitreous chamber (see Fig. 1.42). The maximum attainable *pressure level* depends on the resistance of the zonulocapsular diaphragm, whose integrity is an essential prerequisite for nucleolysis by expression.[25]

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[25] This method is contraindicated if the zonule has been weakened as a result of trauma, pseudoexfoliation, or previous vitrectomy close to the zonule.

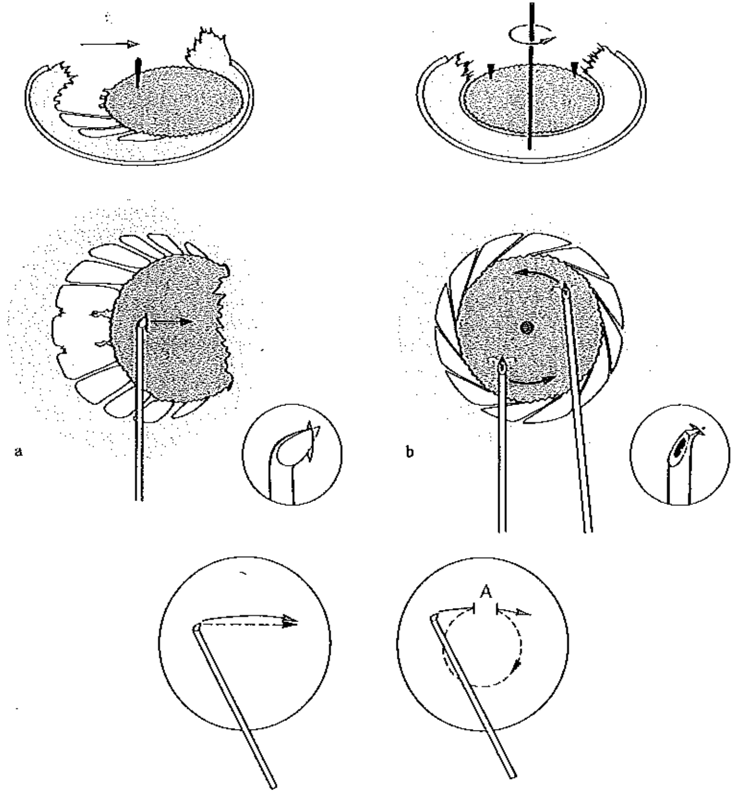
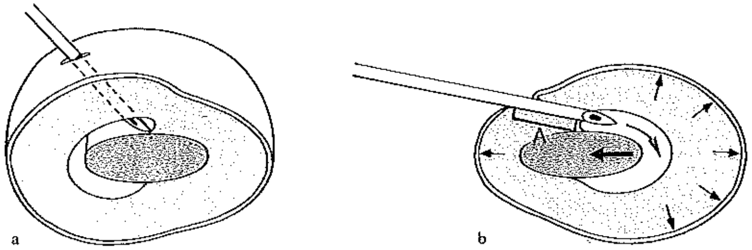


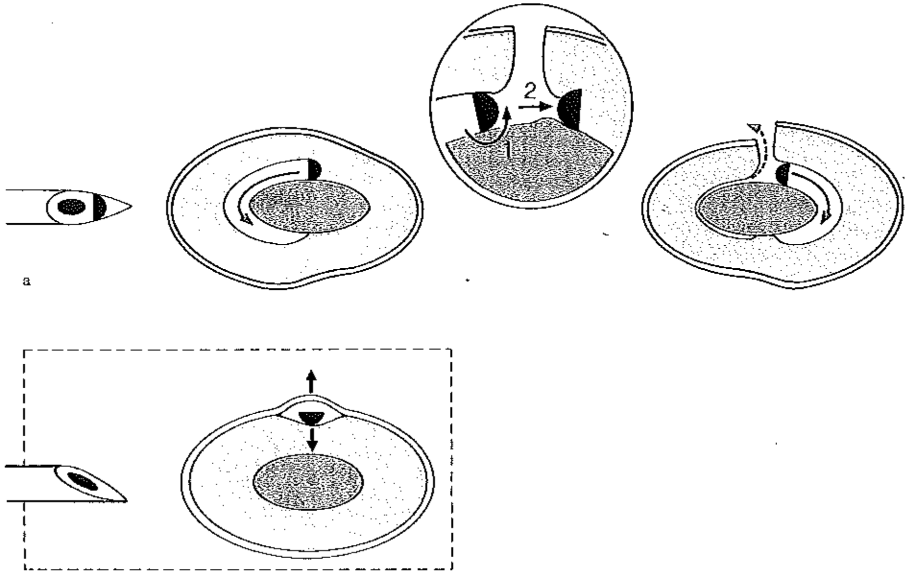
Fig. 8.47. Nucleolysis by the direct application of forces. *Top*: Cross-section through the nucleus; *center*: Top view of the nucleus; *bottom*: Diagram of motion.

a *Lateral motion*: The nucleus is engaged with a cystitome whose blade offers the highest resistance when moved *laterally* (i.e., whose *lateral* surfaces are blunt, see *inset*). The lateral motion of the nucleus ruptures the connections between the nucleus and cortex on one side; on the opposite side pressure is exerted on the cortex, which is either compressed or pushed aside. *Bottom*: The arc of a swiveling motion about a pivot at the entry site (*red arrow*) is nearly congruent with the direction of the lateral shift of the nucleus it should produce.

b *Rotation*: The nucleus is engaged with the bent tips of infusion cannulas that act as blunt instruments when *advanced* or *withdrawn* (see *inset*), and the nucleus is rotated to rupture its cortical attachments. Tension is exerted all over the cortex, but no pressure. The volume distribution within the capsular bag remains unchanged. *Bottom*: A swiveling motion of the cystitome produces a rotational movement about the entry site, but the true goal of the maneuver is rotation about the center of the nucleus (which has a much smaller radius). The arcs of both movements coincide for only a short distance (*A*). Therefore, rotation with only one cystitome should be done in very short increments, since larger movements would place undue stress on the zonule. Maintaining the axis of rotation at the center of the nucleus is made easier by the simultaneous use of two cystitomes



8.48 a b



a b

8.49

Fig. 8.48. **Nucleolysis by hydrodissection,** basic technique.

a A cannula is passed through the capsulotomy into the interior of the lens. Fluid injection creates a pressure chamber in the potential space entered by the cannula opening.

b Longitudinal section. The pressure that can be produced in the pressure chamber is limited by the quality of the seal around the cannula. This depends largely on the size of the capsule opening, the ability of the cortical substance to form a seal around the cannula, and the length of cortex traversed by the cannula (*A*). As pressure builds up in the newly created intralenticular pressure chamber, it compresses the cortex and presses it against the capsule

Fig. 8.49. **Nucleolysis by hydrodissection,** practical application.

a Cross-section. *Left*: The cannula opening faces laterally in the target layer so that the fluid can spread along the lens fibers. *Inset*: For injection toward the opposite side, the cannula is turned (*1*) and pressed tightly against the fibers on that side (*2*). *Right*: This allows fluid to drain from the previously injected chamber. Meanwhile a new seal is established around the cannula for the second injection, increasing the outflow resistance so that a new pressure chamber can form.

b If, in contrast to a, the cannula were inserted superficially with its opening facing the capsule, hydrodissection would effect a corticolysis instead of nucleolysis[27]

The effects of **hydrodissection**, by contrast, are confined to the capsular bag. The injected fluid creates an artificial *pressure chamber* between the nucleus and cortex, which ruptures the connections through its expansion (Fig. 8.48a). The *maximum attainable pressure level* is limited by the resistance of the capsule alone.[26] This factor also limits the volume of fluid that can be injected. It may be necessary to remove fluid from spaces already created before more fluid can be injected into new regions (Fig. 8.49). The *pressure level attainable in practice* depends on the outflow resistance, i.e., on the quality of the seal around the injection cannula (Fig. 8.48b). The injection of *watery fluid* for hydrodissection expands the interspaces among the lens fibers and merely loosens the nucleus, requiring that other means be used to complete the nucleolysis.[28] A complete and continuous corticonuclear interspace can be formed by the injection of *viscoelastic material.*[29]

A major difference between nucleolysis by hydrodissection and the other methods is that hydrodissection does not loosen the *cortex*, but presses it firmly against the capsule. As a result, the cortex can pose an additional obstacle to subsequent delivery of the nucleus unless a preliminary "corticotomy" is carried out.

Aligning the Nucleus for Delivery

Whereas the proper lens alignment for an intracapsular delivery is determined by the location of gaps in the zonule, the optimum alignment of the nucleus in an extracapsular delivery is determined largely by the *frictional resistances* between the rough nucleus, the adjacent tissue surfaces, the pupil margin, and the incision. The rationale for minimizing these resistances is to increase the mobility of the nucleus, thereby reducing the force needed for its delivery.

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[26] The condition of the zonule is irrelevant in this method. Hydrodissection is appropriate for the foregoing cases where expression would be contraindicated.

[27] This achieves the opposite of the planned nucleolysis, which aims at separating the nucleus from the cortex to facilitate the delivery. Instead, it is likely that the cortex will come away with the nucleus when the delivery is attempted, and the larger volume will compound the difficulty of negotiating the capsulotomy, pupil, and corneal incision.

[28] Nucleolysis by hydrodissection is most efficient if combined with simultaneous locomotion so that the nucleus can move forward while being loosened. If this is impossible, as in endocapsular procedures, hydrodissection is less effective.

[29] The reflux resistance of viscoelastic material being very high, there is a danger of excessive capsular tension and rupture during injection. This can be reduced by initiating the hydrodissection with watery fluid, allowing the fluid to drain, and then separating the remaining fiber attachments with viscoelastic material.

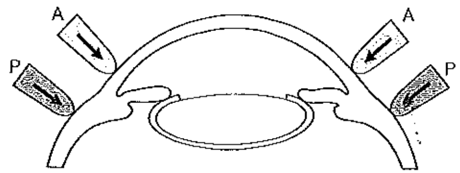


Fig. 8.50. **Locomotive and aligning function of expressors.** Depressors applied to the limbocorneal area serve mainly to align (*A*) the emerging nucleus, while depressors applied more posteriorly to the sclera (*P*) exert pressure on the vitreous chamber (see Fig. 1.42c) and mainly support locomotion of the nucleus

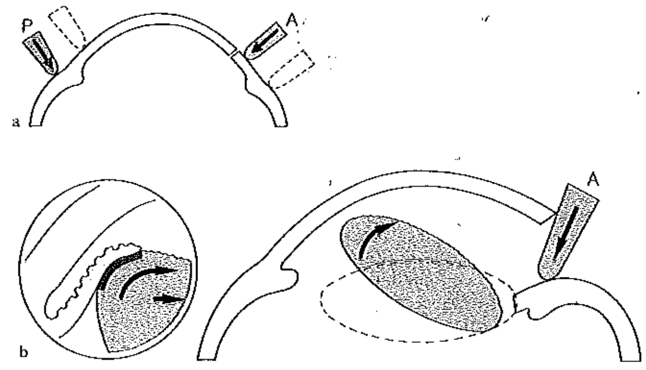


Fig. 8.51. **Tumbling the nucleus for delivery by expression**

a The locomotor depressor *P* is placed inferiorly on the sclera so that it does not hinder the tumbling maneuver. Superiorly the aligning depressor *A* is applied to the limbocorneal zone to restrict upward movement of the superior pole of the nucleus.

b While gliding with its smooth posterior surface past the undersurfaces of the iris and cornea, the nucleus moves away from the iris and cornea (*inset*)

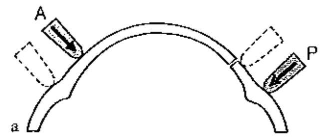
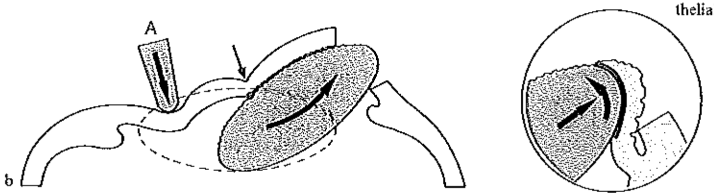


Fig. 8.52. **Delivery of the nucleus by sliding with elevation of the corneal lip**

a The lower expressor (*A*) performs an aligning function by restricting upward motion of the inferior pole of the nucleus. The upper depressor (*P*) is applied to the sclera and raises the vitreous pressure.

b While the superior pole of the nucleus is upraised, it glides tangentially past the undersurface of the iris; but in contrast to Fig. 8.51, it is directed toward the iris. The rough upper surface of the nucleus faces the corneal hinge fold. The longer the nucleus glides past this fold (i.e., the smaller the corneoscleral incision and hence the closer the hinge fold is to the superior limbus), the greater the risk of endothelial injury (see also Fig. 5.20 and 5.21)



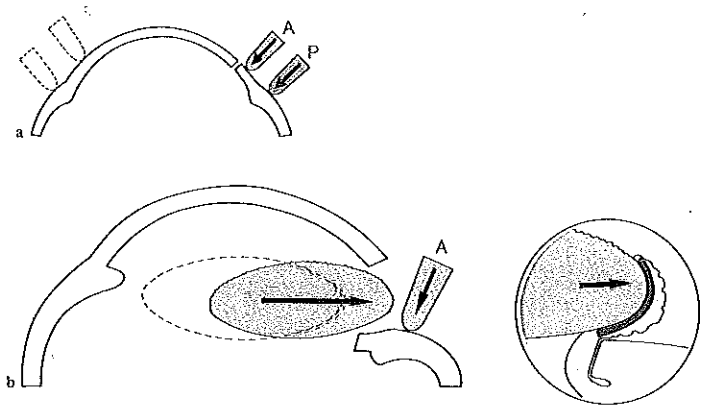


Fig. 8.53. **Delivery of the nucleus by sliding with depression of the lower lip of the corneal wound**

a Both depressors are applied at the lower wound lip. One depressor (*A*) is applied close to the limbus and depresses the lower corneal wound lip to align the nucleus. A second depressor applied to the sclera (*P*) serves to regulate the pressure.

b The nucleus is expelled horizontally. If the pupil is not wide enough it engages directly against the posterior surface of the iris (*inset*). The resistance there is overcome either by retracting the iris with a small hook or by switching momentarily to the technique in Fig. 8.52, i.e., depressing the inferior pole of the nucleus to raise the superior pole (see also Fig. 8.59d)

In delivery by **tumbling**, the *opposite pole* of the nucleus presents first. As the nucleus is tumbled toward the incision, it slides tangentially along the iris and posterior corneal surface. There is relatively little friction, however, because the nucleus moves away from those tissue surfaces and because it presents its smooth posterior face to them (Fig. 8.51).[30]

The pathway for a **sliding delivery** is cleared either by lifting the upper corneal wound lip or by depressing the lower lip. **Raising** the corneal wound margin involves less rotation of the nucleus than tumbling (Fig. 8.52). Significant iris friction can occur in this maneuver, because the nucleus moves *toward* the iris as it glides along its posterior surface. Friction with the posterior corneal surface is a risk if the cornea buckles into a stiff *hinge fold* that scrapes against the rough surface of the nucleus.

In sliding delivery by **depression** of the lower lip of the incision, the nucleus is not rotated from its anatomic level, and it does not touch the posterior corneal surface (Fig. 8.53). If the pupil is *large*, resistance to the delivery is very low. But if the pupil is *small*, the nucleus may move directly toward the posterior iris surface and become entangled there.

The alignment of the nucleus can be controlled directly in *extraction*. In *expression* it is controlled indirectly by increasing or decreasing the resistance along specific paths. Thus, the instruments used in the expression serve two functions: to supply the forces necessary for locomotion, and to control the direction of lens motion. Which effect is predominant depends on the site of instrument application (Fig. 8.50).

With regard to the **choice of alignment** in a given case, the *tumbling* maneuver is facilitated by a nucleus that is approximately spherical. Tumbling may be considered if the incision is placed well corneally, for in this situation tumbling will produce less friction than a sliding delivery with elevation of the corneal flap. The sliding delivery with *depression of the lower wound lip* creates the least friction, provided the pupil is large.

Viscous or viscoelastic materials can be applied as *surface coatings* to reduce friction. Viscoelastic material can also be used as a permanent *spatula* to retain the nucleus in a given alignment even while the expressors are being removed.

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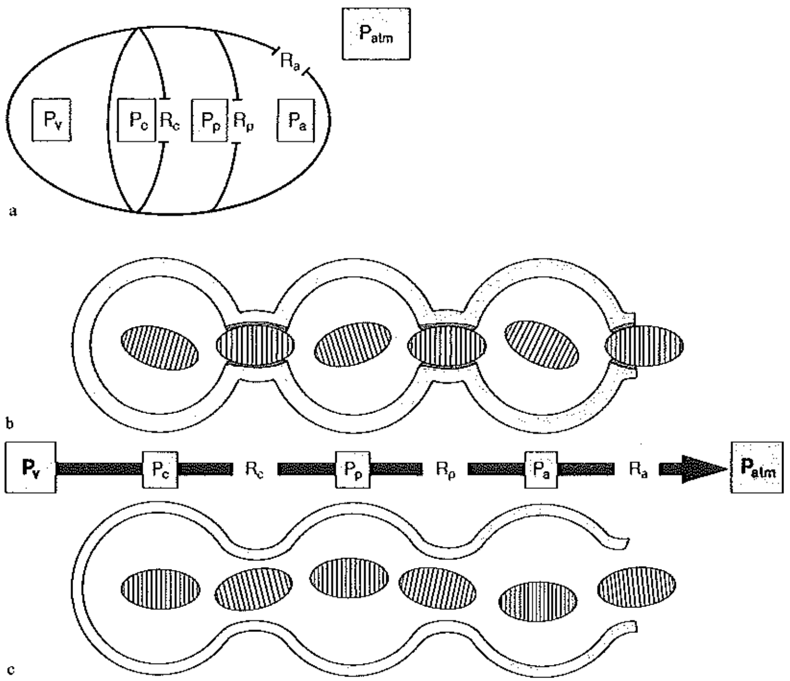
[30] The anterior side of the nucleus may be rough from the previous manipulations. But the posterior side has just been detached from the cortex and has a smoother surface.



Locomotion

Locomotion consists of two phases: passage through open spaces and passage through narrow openings. As each phase involves different resistances, each requires the application of different locomotive forces.

When the nucleus passes through open spaces in the eye, the resistances to locomotion are negligibly small, so minimal force is required. By contrast, the delivery encounters high resistance at **narrow openings**, so much larger locomotive forces are required. The major difference, however, is that the nucleus behaves as an independent loose body while in *open spaces* and moves only when the forces are applied to the nucleus itself. But in *narrow openings* the nucleus effectively becomes part of the wall of the compartment, so movements raise space-tactical problems that require the proper coordination of pressure and resistance. Forces no longer act just on the nucleus, but in all portions of the compartment. Both phases may occur in a sequential, alternating fashion (Fig. 8.54).

In locomotion by **extraction**, the nucleus is grasped with *locally applied instruments* such as hooks, forceps, suction cups, or cryoprobes. Extraction is easily accomplished through open spaces even with a nucleus of low compactness. But extraction through narrow openings may produce a *negative pressure* in the chamber from which the nucleus emerges. This vacuum increases the resistance to locomotion through the narrowing, in which

Fig. 8.54. **Sequence of pressure phases during locomotion**

a Schematic representation of the delivery path from the pressure chamber of the capsular bag (P_c) through the capsulotomy (R_c) into the retropupillary pressure chamber (P_p), through the pupil (R_p) into the anterior pressure chamber (P_a), and through the incision (R_a) to the outside into the "atmospheric pressure chamber" ($P_{atm}=0$).

b When there are narrow openings along the path of the delivery, phases of low pressure will alternate with phases of higher pressure. Locomotion through narrow passages is driven by the pressure gradients between the vitreous space, anterior chamber, and the outside environment. For locomotion through open spaces, other forces (i.e., extractors) must act on the nucleus to move it forward.

c When the openings along the delivery path are large, all locomotion involves a "pressureless" passage through open spaces

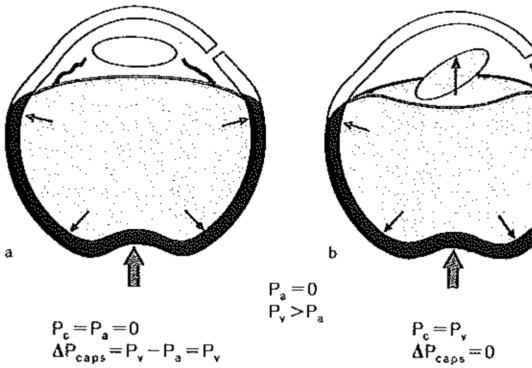


Fig. 8.55. **Space-tactical aspects of delivery by expression.** The pressure in the vitreous chamber (P_v) is higher than the pressure in the anterior chamber (P_a).

a If the capsulotomy or capsulectomy is large, the outflow resistance from the capsular bag (which behaves here as a precapsular chamber) is zero, and the pressure in the precapsular chamber (P_c) equals the pressure in the anterior chamber P_a (when the anterior chamber is open, it equals the outside pressure $P_a=0$). Thus, the pressure in the space in front of the posterior lens capsule is P_a, and P_v behind it; the posterior capsule is exposed to the full effect of the pressure differential.

b With a small capsulotomy, the emerging nucleus can occlude the opening. Since the pressure in the precapsular chamber can equal the vitreous pressure up to the moment at which the largest cross-section of the nucleus emerges through the capsulotomy, the posterior capsule is not exposed to a pressure differential until that moment

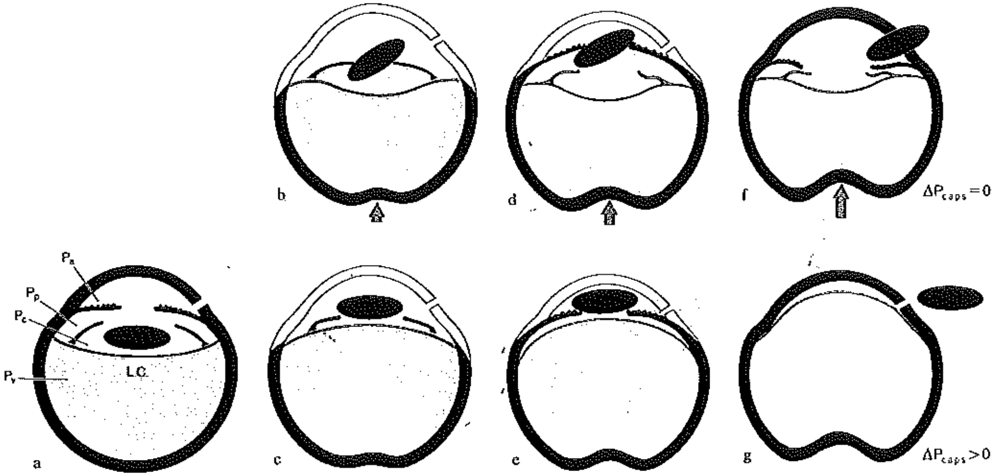


Fig. 8.56. **Stresses on the posterior lens capsule in the various phases of expression.** *Top row*: High-pressure phases through narrow openings; the posterior capsule (L. C.) is not exposed to a pressure differential. *Bottom row*: Low-pressure phases through open spaces; the posterior capsule is exposed to a large pressure differential.

a Nucleus in the capsular bag.

b Passage of the nucleus through the capsulotomy.

c Nucleus in the retropupillary chamber.

d Passage through the pupil.

e Nucleus in the anterior chamber.

f Passage through the corneal incision.

g Completion of locomotion. The nucleus is now outside the eye

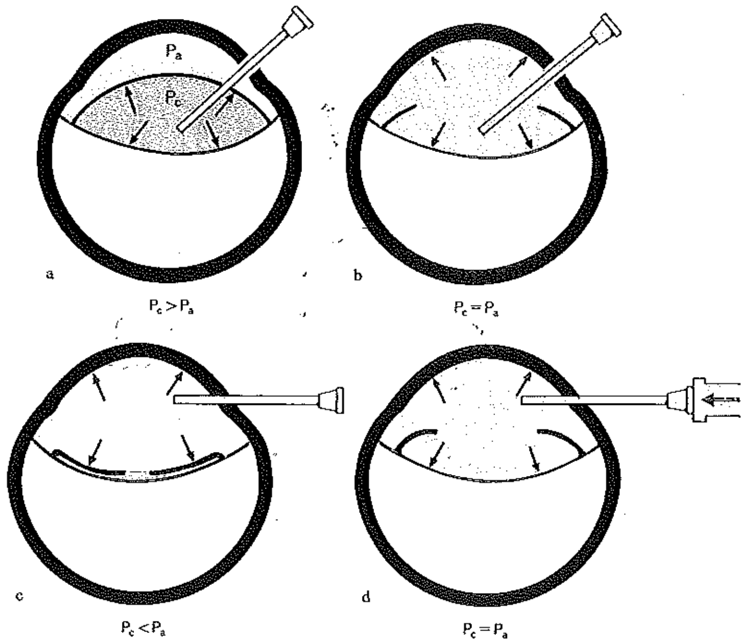


Fig. 8.57. **Space-tactical aspects of irrigation for expulsion of the nucleus.** The pressure in the anterior chamber (P_a) during irrigation is greater than that in the environment and greater than or equal to that in the vitreous chamber (P_v).

a, b Injection into the capsular bag.
c, d Injection into the anterior chamber.

a Injection into the capsular bag through a small capsulotomy: The pressure in the capsular bag (P_c) can exceed that in the anterior chamber (P_a).

b Injection into the capsular bag through a large capsulotomy: P_c equals P_a.

c Injection into the anterior chamber with a small capsulotomy: P_a exceeds P_c, and the capsular bag collapses.

d Injection into the anterior chamber with a large capsulotomy: P_c equals P_a

case the nucleus must be very compact for an extraction to succeed.

Locomotion by **expression** involves a rise of *pressure* in *the vitreous chamber.* In the phases where resistance is low, the elevated pressure serves merely to raise the diaphragm, thereby reducing the space available for the nucleus and forcing it to move along paths of least resistance; a small pressure increase will be sufficient. But in the high-resistance phases where the nucleus must traverse sites of narrowing, it is necessary to raise the pressure in the chamber until it becomes high enough to forcibly expel the nucleus.[31]

The danger posed to the *posterior lens capsule* by this maneuver depends on the pressure difference between the space in front of the posterior lens capsule ("precapsular chamber system")[32] and the space behind. This pressure difference in turn depends on whether the precapsular chamber is part of the vitreous pressure system or part of the anterior-chamber pressure system (Fig. 8.55). The two locomotive phases differ in this regard: The precapsular chamber belongs to the pressure system of the *anterior chamber* while the nucleus is passing through *open spaces*, but it belongs to the *vitreous* pressure system while the nucleus passes through *narrow openings*.

This fact has several implications. As long as the nucleus can *occlude the narrow opening*, the pressures in the vitreous chamber and precapsular chamber are equal, so the lens capsule is not exposed to a pressure differential. But once the nucleus has *passed through* the narrow opening, the pressure in the precapsular chamber falls precipitously, and the posterior capsule is suddenly exposed to the full effects of the pressure differential (Fig. 8.56). Thus, there is no danger to the capsule before the largest diameter of the nucleus has traversed the narrow opening, regardless of the degree of pressure applied. But as soon as the largest nuclear diameter emerges, the capsule comes under tension abruptly and may rupture.

This principle is reflected in the **safety rule for expression of the nucleus**: The impending *danger* of capsule rupture is signified by an increase in the force needed for locomotion. The *moment* of rupture occurs just when this force ceases to be necessary.

The surgeon can anticipate this danger whenever he tries to compel locomotion by applying greater pressure.[33] He can reduce the risk of capsule rupture by discontinuing the application of force at the proper time, i.e., just *before* the largest cross-section of the nucleus traverses the narrow opening. He may then enlarge the opening to provide a path of lower resistance.[34]

In **expulsion**, locomotion of the nucleus is accomplished by *fluid injection* (Fig. 8.57). When the nucleus moves through an open space, the motivating force is produced by the fluid stream and thus obeys hydrodynamic laws. But in narrow openings a pressure chamber forms behind the nucleus, and this pressure, which derives from the increased resistance, supports the movement of the nucleus against this very resistance. The pressures do not attain the values that develop in an expression, because the irrigation cannula that has been introduced prevents watertight occlusion of the opening. Accordingly, expulsion carries less danger of posterior capsule rupture. The main complication in fluid expulsion is *entanglement* of the nucleus on surface irregularities along the passageways. Whereas the volume of the anterior chamber is reduced in expression, in expulsion it is increased. This allows much room for uncontrolled movements of the nucleus, a tendency that may be aggravated by the eddy currents that form in the forcibly injected fluid.[35] *Control* of the expulsion is geared toward producing a uniform stream (i.e., avoiding eddy flow by using a large-gauge cannula) and preventing entanglement by using a glide to direct the nucleus toward the incision.

The general **safety strategy** in locomotion is to minimize the *pressure differential* at the posterior lens capsule. Basically this means establishing at the outset a path of low resistance for delivery of the nucleus – a sufficiently large capsulotomy, pupil, and incision – so that virtually all phases of the locomotion can occur through open spaces (see Fig. 8.54c). If that is not possible, the surgeon must be prepared to take appropriate measures *before the largest cross-section* of the nucleus slips through a narrow opening; he must respond quickly by releasing pressure on the vitreous in time.

Examples of Techniques for Delivering the Nucleus

In contrast to intracapsular deliveries, *expression* is less hazardous than extraction in an extracapsular delivery because the diaphragm is less vulnerable. *Extraction*, on the other hand, is more difficult because grasping instruments cannot grip the nucleus as securely as they can an intact lens capsule.

The selection of expression or extraction in a given case will depend on the stress tolerance of the diaphragm and also on the compactness of the nucleus. It may be appropriate to use *separate techniques* for negotiating the capsulotomy, pupil, and incision, because the size (resistance to delivery) and direction (alignment for delivery) may be different for each of these apertures.

The examples in Figs. 8.58–8.60 illustrate extracapsular delivery by *pure expression*, *pure extraction*, and *mixed techniques*.

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[31] This is analogous to spitting out a cherry pit. In the low-resistance phase the pit is carried through the open oral cavity to the lips with the tongue; it may then be released with slight force if the lips are separated (i.e., if the diameter of the aperture is larger than the pit). Conversely, a high-resistance phase is produced by pressing the lips tightly together. Now the tongue plays no role in expulsion of the pit, which is effected by a high pressure within the oral cavity.

[32] The entire pressure system governing the pressure in front of the posterior capsule is termed the "precapsular chamber." Depending on the resistances at the capsulotomy, the pupil, and the corneoscleral incision, the precapsular chamber may comprise the capsular bag, the retropupillary chamber, the anterior chamber, or the extraocular atmosphere.

[33] The "pressure test" is an important monitoring aid for the instructing surgeon assisting a novice. By applying a palpating instrument to the sclera, the surgeon can detect the pressure rise, recognize that danger exists, and give appropriate instruction.

[34] E.g., by extending the capsulotomy, enlarging the pupil (see Figs. 7.36–7.38), or enlarging the corneal incision.

[35] Eddy currents are most apt to form when a narrow-gauge cannula is used. A high inflow rate is then needed to develop a sufficient pressure, and this implies high flow velocities.

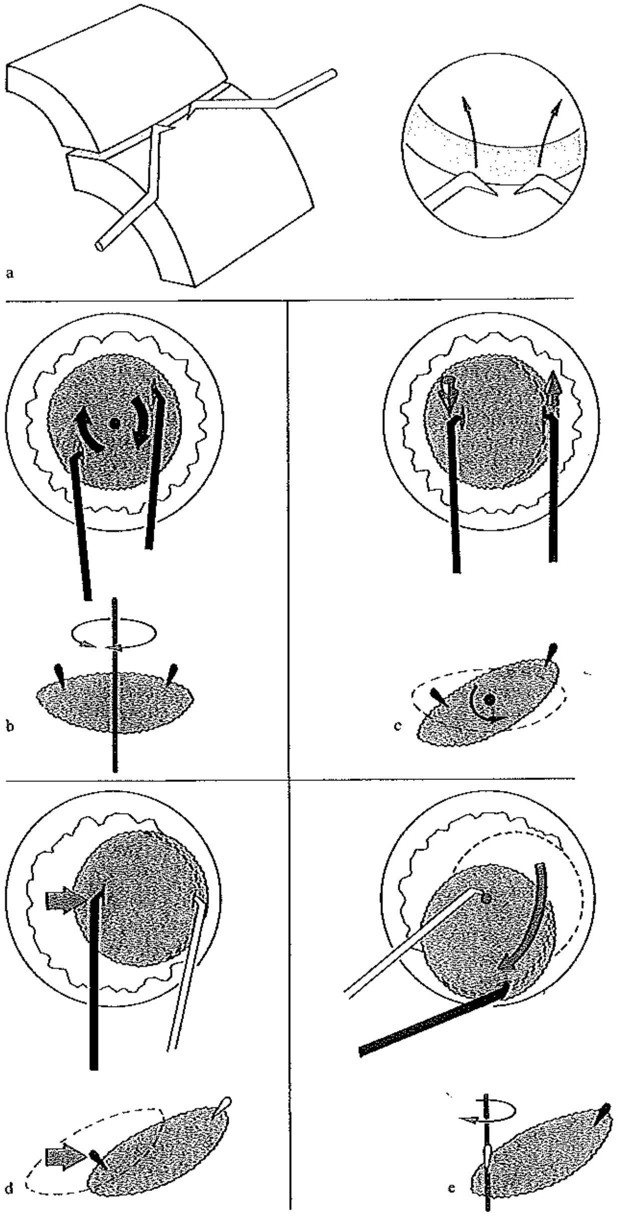


Fig. 8.58. Extraction of the nucleus using two infusion cannulas with angled tips

a Introduction of the instruments: The cannulas are passed into the anterior chamber at the center of the incision and are guided from there in divergent directions. The tips face laterally with the blunt ends leading until the nucleus is reached (see also Fig. 8.36c). There the tips are turned downward.

b The sharp tips are hooked into the midperiphery of the nucleus, which is mobilized by rotation about its vertical axis (see Fig. 8.2d).

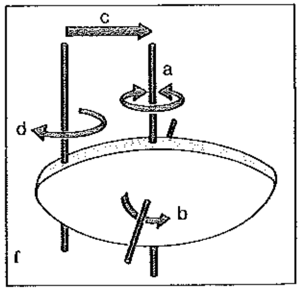
c The right pole is delivered into the anterior chamber by tipping the nucleus about a transverse axis. For this the left hook is pressed downward slightly, while the right hook moves upward with the opposite pole.

d Once the right pole has crossed the iris plane, the nucleus is shifted to the right until the left hook is at the center of the pupil.

e At this point the left hook functions passively as an eccentric pivot for wheeling the nucleus out of the eye with the right hook.

f Review of the extraction maneuvers. The letters correspond to the figure labels and designate the rotational axes and lateral shifts of the various phases.

Hooks in black: Active force transmitters
Hooks in white: Passive hooks



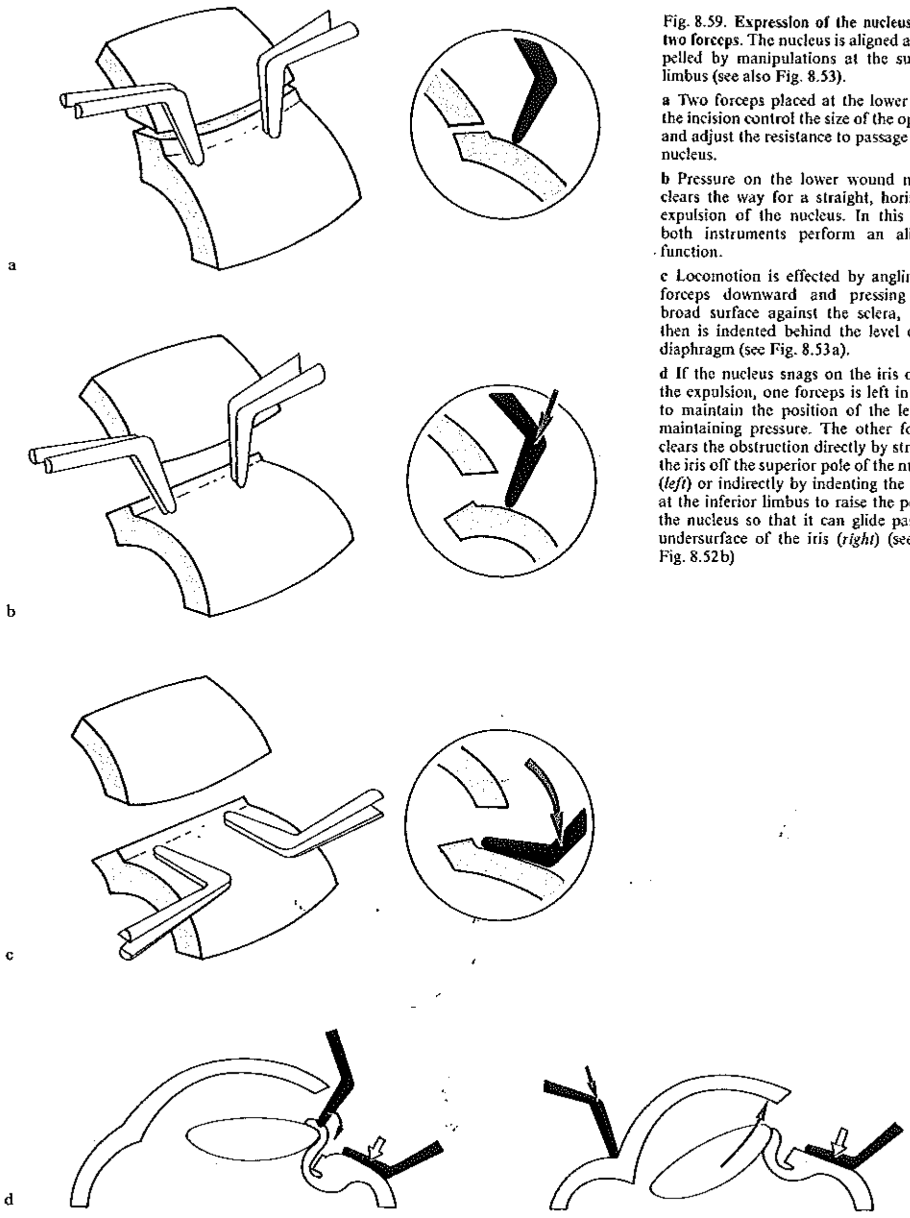


Fig. 8.59. Expression of the nucleus using two forceps. The nucleus is aligned and expelled by manipulations at the superior limbus (see also Fig. 8.53).

a Two forceps placed at the lower lip of the incision control the size of the opening and adjust the resistance to passage of the nucleus.

b Pressure on the lower wound margin clears the way for a straight, horizontal expulsion of the nucleus. In this phase both instruments perform an aligning function.

c Locomotion is effected by angling the forceps downward and pressing their broad surface against the sclera, which then is indented behind the level of the diaphragm (see Fig. 8.53a).

d If the nucleus snags on the iris during the expulsion, one forceps is left in place to maintain the position of the lens by maintaining pressure. The other forceps clears the obstruction directly by stroking the iris off the superior pole of the nucleus (*left*) or indirectly by indenting the sclera at the inferior limbus to raise the pole of the nucleus so that it can glide past the undersurface of the iris (*right*) (see also Fig. 8.52b)

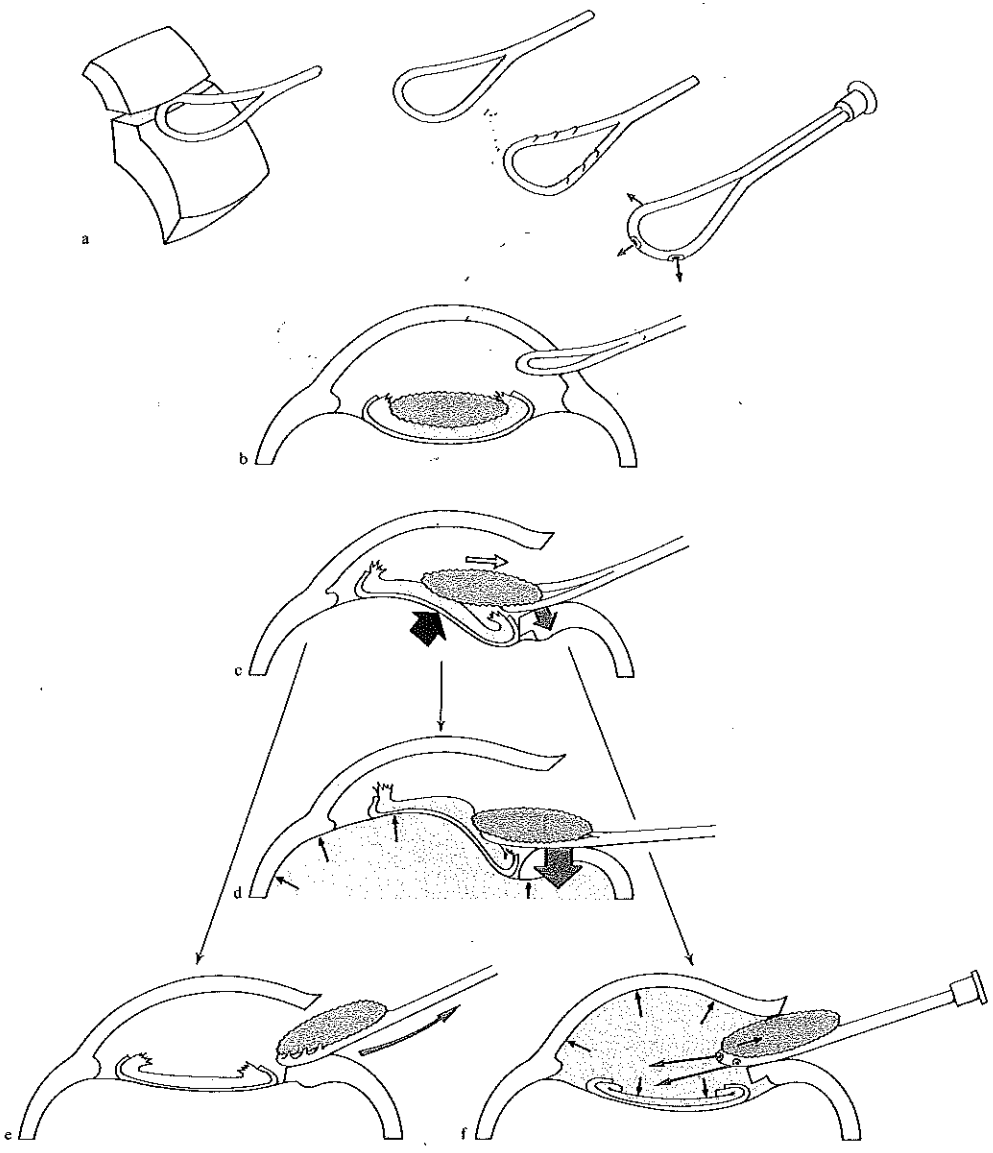


Fig. 8.60. Combined expression and extraction techniques (with a lens loop)

a Different types of loop serve different functions: *Left*: Smooth loop as a glide for a nucleus delivered by expression; *Center*: Serrated loop with back-angled teeth for extraction; *Right*: Irrigating loop for expulsion.

b, c The initial phase of the maneuver is the same for all three instruments: The nucleus is expressed until its upper pole engages against the loop.

b Insertion of the loop into the eye. The front end of the loop is inserted so that it does not block upward motion of the superior pole of the nucleus.

c The lower lip of the incision is depressed with the loop to initiate the expression. The superior pole of the nucleus glides onto the loop, which serves both an aligning and a locomotive function (analogous to the forceps in Fig. 8.59c).

d–f Further locomotion differs for each type of loop.

d Pure expression. Further depression of the smooth loop elevates the diaphragm and expels the nucleus onto the loop, which acts as a glide to prevent entanglement of the nucleus in the iris and corneal ledge.

e Extraction. The nucleus is expressed until the teeth of the serrated loop can engage its posterior surface. The loop is then withdrawn, extracting the nucleus.

f Expulsion. The irrigating loop is immobile and maintains depression of the wound margin, while fluid is injected to raise the pressure in the anterior chamber and expel the nucleus. *Note*: If expulsion is done through a small capsulotomy (as in Fig. 8.57a), the capsular bag will function as the expelling pressure chamber. Because the volume of the bag is small and the resistance at the capsulotomy is relatively high, the volume and pressure of the injection required for expulsion are smaller than with a large capsule opening (as in Fig. 8.57b)

8.3.3 Phacoemulsification

In phacoemulsification the substance of the lens nucleus is broken up into very small particles and removed by aspiration. A phacoemulsifying instrument must perform three functions (Fig. 8.61a): fragmentation of the material (*ultrasonic vibration*), removal of the material (*aspiration*), and replacement of the aspirated volume (*infusion*).

Because of the heat generated by the ultrasonic vibrator, the instrument tip is cooled by a fluid stream. This **cooling stream** must continue to flow even when the aspiration port is obstructed and outflow through the aspirating system stops.[36] An uninterrupted flow therefore requires a reliable *outlet* that is independent of the aspiration. A deliberate "leak" formed at the site of insertion of the phacoemulsifier may serve this purpose. Such a communication with the outside may depressurize the anterior chamber (see Fig. 1.5c) and there is a danger of chamber collapse unless the cross-section of the outlet is precisely matched to the available infusion capacity. Spacetactical *safety control* requires close monitoring of the position of the emulsifier at this opening in order to keep its cross-section constant during all maneuvers (see Fig. 1.14).

Cooling requirements at the site of action demand that the fluid be infused as *close* to the ultrasonic tip as possible. Consequently the cross-section of the emulsifier is enlarged just behind the tip by the extra cross-section of the infusion line. The trailing part of the instrument is correspondingly thicker than the channel cut into the substance of the nucleus, and the depth of penetration is limited by the distance of the infusion sleeve from the tip (Fig. 8.61).

If the nuclear material is to be emulsified effectively, it must not be pushed aside by the vibrating tip, i.e., it must be affixed to the tip. There are **two basic methods** of accomplishing this fixation: by inertia of the nucleus (with *aspiration in flow*) and by suction (with *aspiration by occlusion*) (see Fig. 2.26).

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[36] In a controlled-flow system, infusion ceases when the aspirating port is obstructed. Unplanned occlusion during aspiration means the loss of cooling capacity. The danger of tissue overheating during ultrasonic vibration, and thus the cooling requirements, depend on the power of the vibrations.

Emulsification by Aspiration in Flow

In this method the aspiration port remains open throughout the emulsification (Fig. 8.63). The vibrating tip is moved along the nucleus, the direction of this movement determining the direction in which the emulsification proceeds (Fig. 8.65b). The nucleus remains stationary.

The *immobility of the nucleus* is an inertial effect based on the mass of the nuclear material (Fig. 8.65a). But this mass dwindles as the emulsification proceeds. To maintain effective emulsification during the entire procedure, the immobility of the nucleus must be reinforced by friction. This friction either may be produced by the anatomic connections between the nucleus and cortex, which should be left intact for as long as possible (avoiding preliminary nucleolysis), or it may be provided by fixation instruments (e.g., spatulas holding the nucleus in place).

Immobility of the lens nucleus is *the criterion for the control* of phacoemulsification in flow. The **power of the vibrations** should be high enough to provide efficient emulsification but low enough to avoid shaking the entire nucleus. Due to concomitant movements of the nucleus, excessive vibration will not improve efficacy and may cause undesired transmission of motion to surrounding tissues. Therefore as the *mass of the nucleus decreases*, the power of the vibrations should be reduced.

The immobility criterion also influences the **speed of the guidance motion**. Moving the tip too rapidly will merely displace the nucleus without improving the efficacy of the emulsification.

The **shape of the instrument tip** for aspiration in flow is not a critical factor during application of the tip to the nucleus. For the subsequent emulsification phase, however, a pointed tip has the advantage of aiding visual monitoring and preventing unintentional occlusion (Fig. 8.62). Additionally, a pointed tip can conform geometrically to narrow spaces and poses less danger when used close to adjacent tissues.

The **position of the sleeve**, i.e., its distance from the vibrator tip, limits the application angle of the instrument to the nucleus. If the tip is directed at too flat an angle, the sleeve will engage against the nucleus and push it away from the vibrating tip (Fig. 8.66c).

In terms of **spatial tactics**, a fluid stream must flow throughout the emulsification in flow. The *pressure level* in the anterior chamber, as determined by the flowthrough parameters (see Fig. 2.26b), lies between the initial and terminal pressures. The *pressure difference* between the chamber and aspiration port is very small (Fig. 8.66d). Since the fluid flow is continuous, adequate tip cooling does not rely on a special outflow path for the cooling fluid (Fig. 8.66e, Fig. 8.67).

The use of an *open aspiration port* involves risks: emulsified particles may be projected at high velocity toward adjacent tissue surfaces (Fig. 8.65c),[37] and mobile surrounding tissues may be inadvertently aspirated (Fig. 8.65d). Thus, successful emulsification by aspiration in flow requires that a *safe distance* be maintained with respect to neighboring tissues.

Emulsification by Occlusion

In emulsification by occlusion, the instrument tip is applied to the nucleus in a way that occludes the aspiration port. *Control* aims at maintaining this occlusion throughout the emulsification (Fig. 8.64). The **shape of the tip** is critical, for it should conform to the surface of the nucleus to be emulsified (see Fig. 8.66a). Otherwise there will either be no occlusion if the nucleus is immobile, or a mobile nucleus will abruptly change its orientation in an unpredictable way and damage adjacent tissues. However, if the nuclear geometry is unfavorable, the ultrasonic vibrator can be used to create **occludability**, i.e., to cut the site of application (in an initial burst of aspiration in flow) to a suitable shape that will permit occlusion without reorientation of the nucleus (Fig. 8.64b).

Once occlusion has been established, suction plays the predominant role. The procedure of emulsification by occlusion is basically an aspiration in which ultrasonic vibration merely serves the adjunctive purpose of creating or maintaining the occlusion. The *tip* can be held *stationary* and the emulsification allowed to proceed by *motion of the nucleus*. This is an important safety factor, for it avoids any motion vectors directed toward surrounding tissues (Fig. 8.65b). *Occlusion of the tip opening* also prevents inadvertent aspiration of adjacent tissues and the projection of emulsified lens particles toward delicate structures (Fig. 8.65c, d).

In terms of **spatial tactics**, the situation is stable due to the absence of an aspirating stream

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[37] Delicate tissues like the corneal endothelium can be protected from particle bombardment by surface-tactical measures (e.g., protective coating of viscous or viscoelastic material).

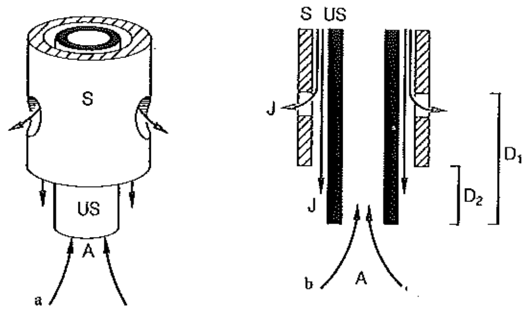


Fig. 8.61. Design of a phacoemulsifier with infusion and aspiration

a The central tube serves as the aspiration channel (*A*) and as the ultrasonic tip (*US*). It is surrounded by a sleeve (*S*) through which fluid is infused. Its front opening serves mainly to cool the vibrating tip, while the side openings add volume for space-tactical stabilization. If one of the openings becomes obstructed by tissue, the other will ensure maintenance of the infusion.

b The distance of the infusion ports (*J*) from the vibrating tip (D_1) determines how far the instrument can be withdrawn from the chamber without compromising its spatial stabilization (i.e., the minimum distance from the access opening at which emulsification can still be performed). The distance D_2 between the end of the infusion sleeve and the tip determines how far the instrument can penetrate into the hole cut by the tip (i.e., the maximum penetration depth into the tissue)

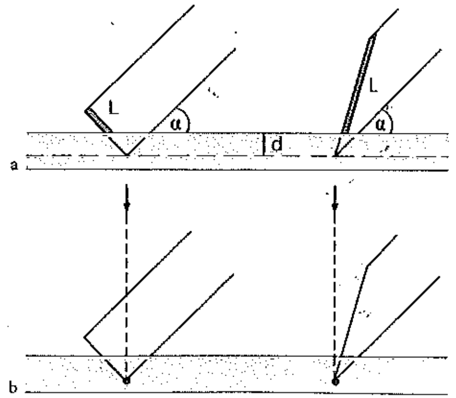


Fig. 8.62. Shape of the instrument tip

a A blunt tip applied at a given angle (α) and given depth of penetration (*d*) experiences greater luminal obstruction (*L*) than a sharply beveled tip. Thus, it is easier to establish occlusion with a blunt tip (*left*), and easier to keep the aspiration port clear with a beveled tip (*right*).

b Visual monitoring of the working area: A blunt tip obscures vision of the tip opening and base of the tissue groove when viewed from above (*arrow*). A beveled tip facilitates visual observation

Fig. 8.63. **Phacoemulsification by aspiration in flow.**
Left: Sequence of steps in procedure; *right*: Instrument motions and switch positions during procedure; *M*: Guidance motions; *A*: Aspiration; *US*: Ultrasonic vibration; *numbers*: Positions of footswitch.[38]

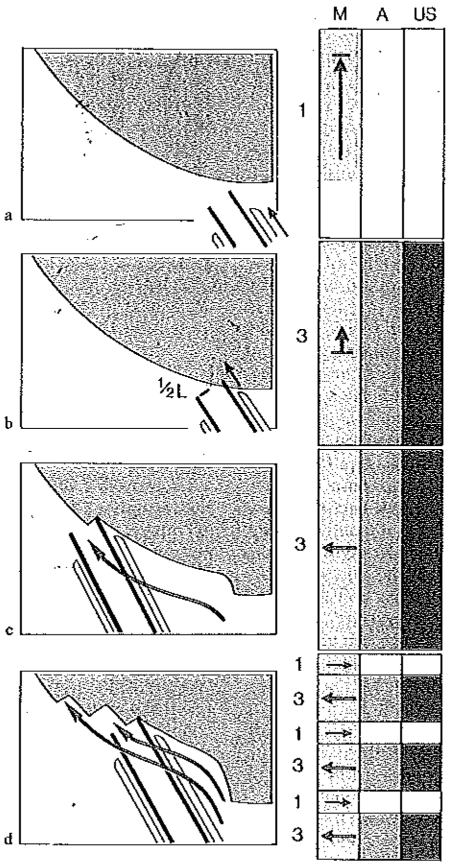
a *Seeking the site of application*: The instrument tip is brought close to the site of election for beginning the emulsification but does not yet touch the nucleus. Monitoring at this stage aims at space-tactical stabilization and thus involves regulation of the infusion and the size of the outflow opening from the anterior chamber (see Fig. 1.4). Aspiration and vibration are not activated. The site of contact with the nucleus is chosen so that the tip can be applied without becoming occluded.

b *Engagement*. The tip is applied to the nucleus while *A* and *US* are simultaneously activated. The tip begins to cut a groove into the substance of the nucleus. *Note*: At least half the lumen (*1/2 L*) should remain clear to avoid occlusion.

c *Peeling*. The tip is guided over the nucleus, moving parallel to its surface (i.e., at a constant tissue depth). The progress of the emulsification is determined entirely by the direction in which the tip is moved. The direction in which the opening faces is of no significance, aside from the stipulation that approximately half the lumen remains clear. *Note*: *A* and *US* must always be activated while the moving tip is in contact with the nucleus; otherwise the tip will displace the nucleus without cutting it. Conversely, *A* and *US* should not be activated unless the tip is moving, since this will have no peeling effect and will increase the risk of unplanned occlusion.

d *Deepening the emulsification*. The tip is lifted away from the nucleus (*A* and *US* turned off!) and moved back before repeating the scaling maneuver. The end of the excavation is "terraced" to reduce the risk of unintended occlusion.

Note: In phacoemulsification in flow only footswitch positions *1* and *3* are used



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[38] In most current systems position 1 is infusion only, position 2 is infusion plus aspiration, and position 3 is infusion, aspiration, and ultrasonic vibration.

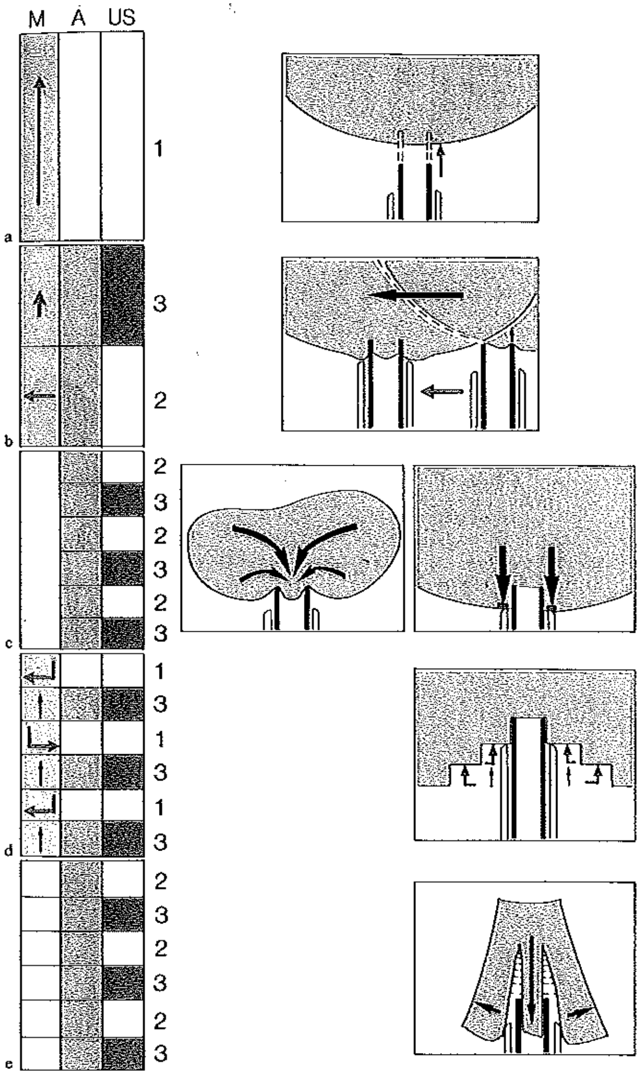


Fig. 8.64. **Phacoemulsification with aspiration by occlusion.** *Left*: Instrument motions and switch positions. *Right*: Sequence of steps in procedure.

a *Seeking occlusion*: The instrument tip is moved into position with *A* and *US* switched off (footswitch position *1*). A site is selected on the nuclear surface where occlusion can be established as soon as the tip is applied.

b *Engagement*. If the nucleus cannot be engaged right away, occludability must be established by a short burst of emulsification in flow. The instrument with the affixed nucleus is then shifted into a region where there is adequate clearance to proceed with emulsification by occlusion (*left*). Only aspiration is switched on during this maneuver to keep the nucleus adherent to the tip (footswitch position *2*).

c *Emulsification*. The instrument is held stationary while aspiration is activated and assisted by short bursts of vibration. If its substance is deformable, the entire nucleus can be emulsified in this way (*left*). If the material is nondeformable, motion of the nucleus toward the tip opening will be checked by the sleeve (*right*).

d *Continuing the emulsification* of nondeformable material. The tip is moved back (with *A* and *US* switched off) and reapplied at an adjacent site so that the excavation is progressively deepened.

e *End of the emulsification*. When the particle has become so small that its sides begin to separate ahead of the sleeve, the emulsification can be completed using the technique for deformable material (c, *left*).

Note: In phacoemulsification by occlusion footswitch position *2* plays an important role

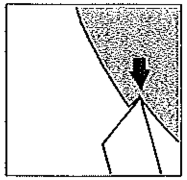
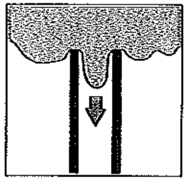
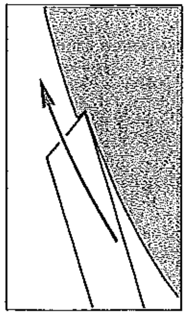
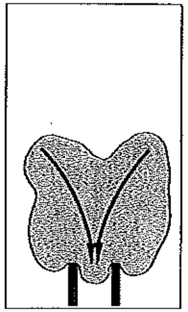
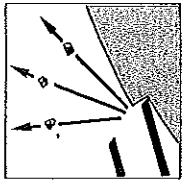
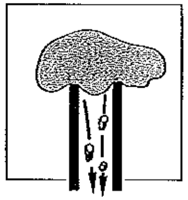
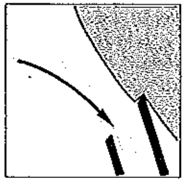
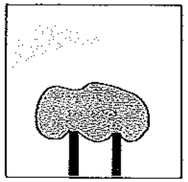
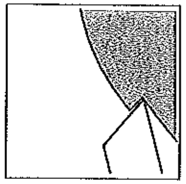
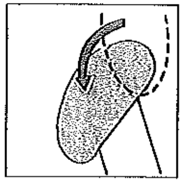
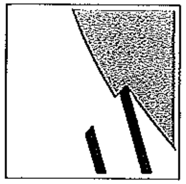
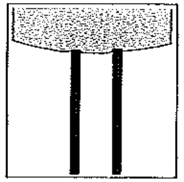
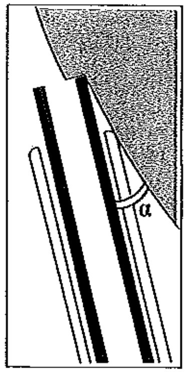
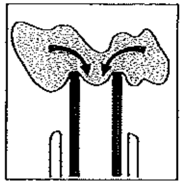
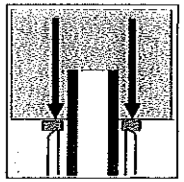
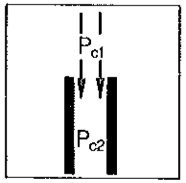
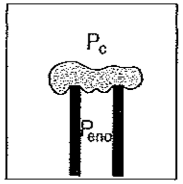
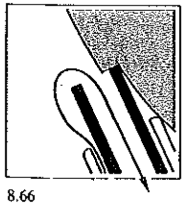
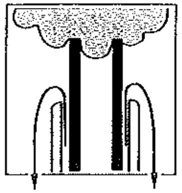
	Aspiration in flow	Aspiration in flow		Aspiration of occlusion	Aspiration of occlusion
a		by the inertia of the material	*Fixation* of the material before the cutting edge	by suction	
b			*Force vectors of motions*		
		by movement of the tip (nucleus immobile)	Progression of the emulsification process	by movement of the nucleus (tip immobile)	
		toward environment	Direction of motion vectors	toward tip	
		yes	Danger of transmitting motion to environment?	no	
c		yes	*Side-effects* Danger of damage from projected particles?	no	
d		yes	Danger of inadvertent aspiration of adjacent tissue?	no	

Fig. 8.65. **Comparison of the two basic methods of phacoemulsification: Mode of operation**

Fig. 8.66. **Comparison of the two basic methods of phacoemulsification: Aspects of instrument design**

	Aspiration in flow	Aspiration in flow		Aspiration by occlusion	Aspiration by occlusion
a		not critical	*Shape of tip* On engagement of the nucleus	critical: reorientation of nucleus on occlusion (see Fig. 2.28)	
b		beveled: favors nonocclusion	Tendency to become occluded (see Fig. 8.62)	blunt favors occlusion	
c		limits angle of instrument application	*Position of sleeve*	with deformable nucleus: not critical with nondeformable nucleus: critical (limits depth of penetration)	 
d		P_c between P_{start} and P_{end}	*Chamber pressure* Pressure level in chamber (P_c)	P_a between P_{start} and P_{atm} (depends on size of outlet for cooling stream)	
		minimal	Pressure difference between chamber and aspiration lumen	maximal	
e		through aspiration port	*Cooling stream* outflow	through separate outlet from the chamber	

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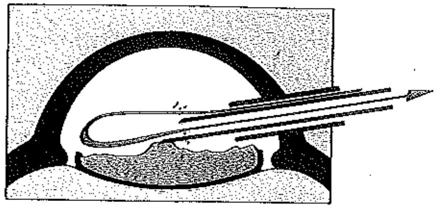

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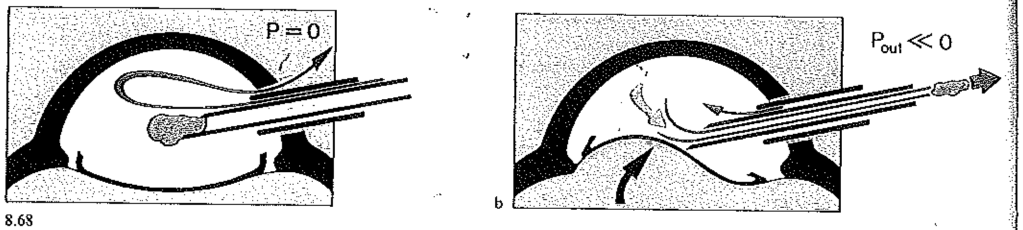

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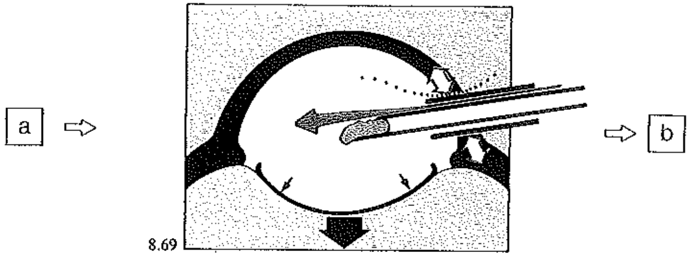

8.69

Fig. 8.67. Spatial tactics for phacoemulsification in flow: A continuous stream of the cooling fluid is maintained through the open aspiration cannula. There is no need for an accessory outlet. Therefore, the access opening can remain watertight during emulsification.

Fig. 8.68. Spatial tactics in phacoemulsification by occlusion

a During occlusion the cooling flow is maintained through an accessory outlet, (e.g., a leaking access opening).

b As the occluding particle has passed through the aspiration cannula, the occlusion ceases. The chamber is suddenly exposed to the strong suction (outflow pressure below zero), and a large fluid volume will abruptly escape. As the chamber collapses, tissue from the vicinity may move into the range of the emulsifying tip

Fig. 8.69. Space tactical safety precautions prior to cessation of the occlusion

At the transition from stage **a** to stage **b** (in Fig. 8.68) a "control stop" is interposed to secure maximal chamber volume: Emulsification and aspiration are interrupted but infusion is maintained. The outflow through the auxiliary outlet is minimized by correcting movements of the emulsifier at the entrance opening (*red arrow*; see Fig. 1.14). Only when the chamber has attained maximum depth (i.e., the position of the lens capsule has been brought back as far as possible) emulsification is activated again for the final removal of the occluding particle

(Fig. 8.66d). The *pressure* in the chamber depends on the size of the additional cooling fluid outlet. If the outlet is sealed off, the chamber pressure equals the initial pressure (see Figs. 1.4a and 2.26a); if it is widely open, the pressure equals atmospheric (see Fig. 1.6a). But in contrast to aspiration in flow, the pressure cannot fall below atmospheric, so there is less danger of chamber collapse (Fig. 8.68a).[39]

The characteristics of both emulsification techniques are summarized in Figs. 8.63 and 8.64. It is apparent that the *control criteria* for each of the techniques are different and are even opposite in many respects. This accounts for the difficulties to be anticipated when emulsification in flow inadvertently changes to emulsification by occlusion, or vice-versa, during the operation.

Thus, the most essential control aspect of phacoemulsification is to maintain the technique that has been selected. If a *change to the other technique* is indicated, the change must be carefully planned; it is imperative that unplanned changes be avoided.

Problems in Changing the Emulsifying Technique

What are the risks associated with an unplanned change from **aspiration in flow to aspiration by occlusion**? First, the nucleus may abruptly change its orientation the moment *occlusion* is established (see Fig. 8.66a), posing a threat to surrounding tissues.[40] Second, the nucleus as a whole may be displaced if the surgeon continues to *move* the instrument (i.e., perform guidance motions) after occlusion has been established. Finally, there is a danger of *overheating* if the additional coolant outlet (which need not be open during aspiration in flow) is not functioning properly once occlusion is established.[41] If unplanned occlusion should occur despite precautions, the surgeon must discontinue any guidance motions at once and switch off the vibration until the situation is again under control.

Unplanned occlusion must be anticipated when the nucleus has become increasingly mobile during emulsification in flow so that it may be drawn abruptly against the aspiration port. Thus, *immobility of the nucleus* must be ensured during emulsification in flow until the surgeon elects a *planned* change to aspiration by occlusion.

The reverse process, an unplanned change from **aspiration by occlusion to aspiration in flow**, has even more serious consequences. The sudden release of the aspiration port creates a massive pressure differential (see Fig. 2.26a) leading to a precipitous pressure drop in the anterior chamber. Chamber collapse may ensue (Fig. 8.68b), and adjacent tissues may be inadvertently aspirated and damaged if the instrument tip is still vibrating at that moment.

But change to aspiration in flow is an inevitable part of any ordinary emulsification by occlusion, representing the *final phase* after the material in front of the tip has vanished.

During the emulsification, loss of occlusion occurs if the vibrating frequency is too high, for then the occluding portion of the nucleus will be abruptly excised and aspirated. If at this point other nuclear material is within reach of the suction, emulsification may proceed. But if adjoining tissue is within the range of the tip, it becomes exposed to the effect of the powerful suction.

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[39] Note: This is true only while the occlusion is intact. Loss of occlusion constitutes aspiration in flow!

[40] Special care must be taken to prevent unintended reorientation of the nucleus when emulsification has sculpted a sharp edge into hard nuclear material.

[41] E.g., if the instrument is held obliquely (as in Fig. 1.14e).

The basic **safety strategy** for aspiration by occlusion, then, is to allow for the *possibility of a sudden loss of occlusion* in each phase of the procedure and forestall its consequences. On the one hand this implies reducing the pressure differential upon loss of occlusion; on the other, providing an adequate safety zone in front of the tip. A low *pressure differential* is obtained with the **short-burst technique.** Maintaining aspiration by occlusion for just a few seconds prevents buildup of high negative pressures. Thus, when occlusion is lost after a short emulsification burst, only a fraction of the force set at the suction pump will become active at the tip. Providing a *safety zone* means maintaining **ample clearance** from adjacent tissues. In this respect aspiration by occlusion requires larger clearances than aspiration in flow. This may seem paradoxical, because occlusion actually protects surrounding structures. However, the safety clearances must provide for an abrupt loss of occlusion, at which point the pressure differential is greater than in aspiration in flow.

Special safety precautions are taken in the final phase of the emulsification, just before occlusion is terminated: Vibration and aspiration are switched off while the infusion is continued. The space-tactical context is checked and optimized, and a *maximum anterior chamber depth* is established by adjusting the position of the instrument at the access opening in order to improve the seal (see Fig. 8.69). Only then the emulsification is completed using short bursts so that both the aspiration and vibration can be switched off immediately upon termination of the occlusion.

Criteria for Selection of the Emulsification Technique

The **indication for emulsification in flow versus emulsification by occlusion** depends on the quality of the lens nucleus and its mobility.

With regard to *emulsifiability*, we can distinguish between compliant nuclear matter that is easily penetrated by the instrument and firm, noncompliant nuclear matter that blocks entry of the sleeve (Fig. 8.64c). Basically, emulsification by occlusion is more appropriate for *deformable* matter, while emulsification in flow is better suited for *nondeformable* matter.

A no less important criterion is the *mobility of the nuclear material.* Only immobile material, whether deformable or nondeformable, can be emulsified in flow, whereas mobile material inevitably will appose to the suction tip and therefore is emulsified by occlusion. This means that both an ideal and an unfavorable emulsification condition exists for deformable and nondeformable nuclei. These conditions cannot be freely chosen but depend on the *anatomic setting* in which the emulsification is carried out: When the phacoemulsification is performed in the anterior chamber, the nucleus has been dislocated from its original position and hence is freely movable within the chamber. When the nucleus is emulsified in situ ("in the posterior chamber"), the anatomic connections between the nucleus and cortex may have remained intact, and the nucleus is immobile. It follows, then, that optimum conditions prevail when deformable matter is emulsified in the anterior chamber, and nondeformable matter is emulsified in the posterior chamber (Fig. 8.70, *red arrows*).

These optimum conditions cannot always be achieved in practice. It can be difficult to mobilize a deformable nucleus and dislocate it into the anterior chamber, because the soft matter is difficult to separate from the cortex. Conversely, a nondeformable nucleus cannot always be kept immobile in the posterior chamber, because it must be mobilized and displaced as the emulsification proceeds in order to present it optimally to the tip. Hence there is no way to avoid working at least temporarily under *suboptimal conditions.*

One suboptimal condition, for example, is the emulsification of *deformable material by aspiration in flow* (e.g., emulsification of a soft nucleus in the posterior chamber). Here occlusion can be prevented by extremely superficial peeling so that only the wall of the tube attacks the nucleus while the lumen remains entirely clear. The nucleus may be held immobile with a spatula.

Another suboptimal condition is the *emulsification by occlusion of nondeformable matter* (e.g., the emulsification of hard nuclear matter in the anterior chamber). Here the technique must allow for the blocking action of the sleeve (Fig. 8.64c), so the emulsification is carried out in small steps that progressively deepen the excavation (Fig. 8.64d). If the noncompliant matter becomes incarcerated at the tip, there are two ways to loosen it again: Short, high-frequency bursts of the vibrator can repel it effectively, but they are safe only if the incarcerated material has sufficient mass to check the recoil. With a small particle it is better to use short bursts of low-frequency vibration to loosen the material and to push it back with a spatula.

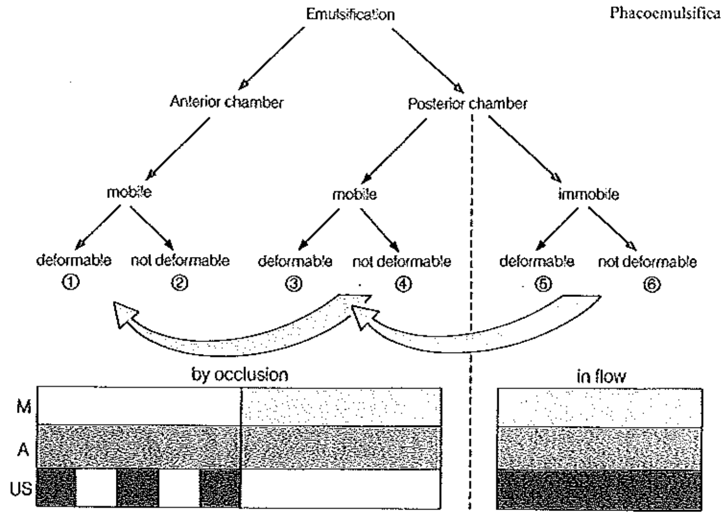

Fig. 8.70. **Decision-making criteria for selecting the emulsification technique.** When emulsification is performed in the posterior chamber, the nucleus is immobile, at least initially. Therefore it is emulsified in flow. This procedure is accomplished most successfully in nondeformable material (*6*), while with deformable matter (*5*) there is a danger of unintended occlusion. If the nucleus has become mobile while in the posterior chamber (*3, 4*), it may either be immobilized there with a spatula, or it may be dislocated forward into the anterior chamber (using aspiration only). Once inside the anterior chamber, the nucleus is mobile. Since it is emulsified there by occlusion, emulsification in the anterior chamber is ideal for deformable nuclei (*1*) but is suboptimal for nondeformable nuclei (*2*). The *red arrows* indicate the optimum emulsification conditions. The *gray arrows* indicate the sequence of steps for a nucleus in the posterior chamber: an immobile nucleus is mobilized and then dislocated into the anterior chamber. First the nucleus is emulsified in flow, and once mobilized it is emulsified by occlusion

Table 8.2. Comparison between planned and unplanned transitions from emulsification in flow (E.i.F.) to emulsification by occlusion (E.b.O.), resp. from E.b.O. to E.i.F.

E.i.F. → E.b.O.		E.b.O. → E.i.F.	
planned start of E.b.O.	unplanned transition	planned end of E.b.O.	unplanned transition
1. *Establish foldability* – remove all hard material	Wrong *moment*: hard material still present	1. *Provide large reserve space* – deepen anterior chamber (see Fig. 8.69)	Wrong *moment*: without sufficient chamber volume
↓		↓	
2. *Establish occludability* – align bevel of tip to contour of nucleus (see Fig. 2.28a+d) – cut material into occluding shape (see Fig. 8.64b)	Wrong *way*: bevel not properly aligned (see Fig. 2.28b+c)	2. *Keep bevel away from vulnerable tissue* – stay in safety zone for E.b.O.	Wrong *place*: beyond safety zone for E.b.O.
↓		↓	
3. *Proceed to E.b.O.* – transfer material to safety zone for E.b.O. (see Fig. 8.73b) – stay put and cut	Wrong *place*: orifice of tip beyond safety zone	3. *Avoid high pressure difference* – use short burst technique	Wrong *way*: long bursts of ultrasound

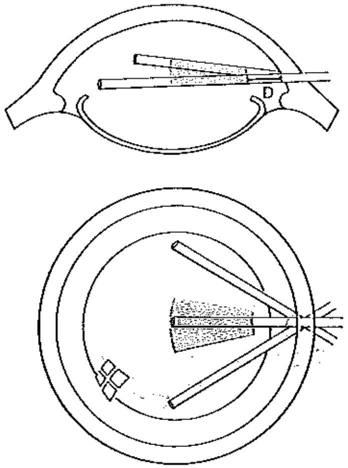

Fig. 8.71. Topographic criteria for the use of phacoemulsification: Safety zones in the anterior chamber. *Gray zone*: Safety zone for aspiration alone; *pink zone*: Safety zone for vibration and aspiration combined.

The nucleus is mobile in the anterior chamber and is emulsified by occlusion. The safety margins must be large enough to ensure that a sudden loss of occlusion will not damage nearby tissues. Aspiration alone poses relatively little risk of damage, so the safety zone is large. Ultrasonic vibration, on the other hand, requires large clearances: The safety zone does not extend past the center of the pupil. Very little deviation upward or downward from the horizontal can be tolerated due to the respective dangers posed to the corneal endothelium and iris. Lateral mobility during vibration is limited to ensure that the outlet for the cooling fluid is not obstructed (see Fig. 1.14e). The minimum distance from the access opening (*D*) at which emulsification can be performed depends on the position of the openings in the sleeve (see Fig. 8.61)

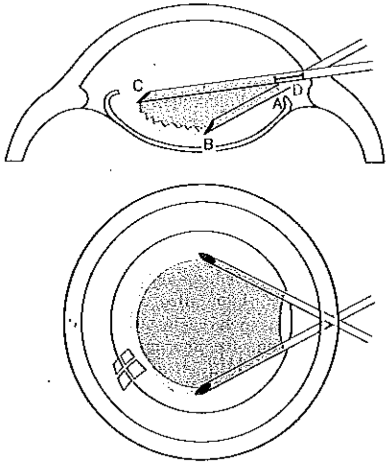

Fig. 8.72. Topographic criteria for the use of phacoemulsification: Safety zone in the posterior chamber. If the nucleus is immobile while in the posterior chamber, it is emulsified in flow. Since this method is not associated with abrupt pressure changes, the necessary clearances are small. Thus the safety zone is large and is practically the same for emulsification (*pink*) as for simple aspiration (*gray*). The start of the safety zone (*A*) and its deep boundary (*B*) are influenced by the location of the corneal incision, the end of the zone (*C*) by the pupil size. (*D*) as in Fig. 8.71

Basic Techniques of Phacoemulsification

In both the anterior and posterior chamber there is a **safety zone** whose boundaries are determined by the clearances that must be maintained with respect to surrounding tissues. As noted earlier, these *clearances* depend on the phacoemulsification technique, emulsification by occlusion requiring greater safety clearances than emulsification in flow. Thus, the safety zone for emulsification in the anterior chamber is quite small (Fig. 8.71). It is larger for emulsification in the posterior chamber, as long as the nucleus is sufficiently immobile for emulsification in flow (Fig. 8.72).

The basic rule is that phacoemulsification is performed *strictly within the safety zone* of the respective chamber (Fig. 8.73b). Nuclear material already within the safety zones is removed first, and then the remaining material is transposed into the safety zones before it is emulsified (Fig. 8.73c, d). Topographically, then, the procedure consists of four phases:

- emulsification within the safety zone for emulsification by aspiration in flow
- nucleolysis
- locomotion
- emulsification within the safety zone for emulsification by occlusion.

There are three basic techniques for phacoemulsification according to the way in which these steps are sequenced and combined:

1. Phacoemulsification in the anterior chamber (Fig. 8.74).
2. Phacoemulsification in both chambers (Fig. 8.75).
3. Phacoemulsification in the capsular bag (Fig. 8.76).

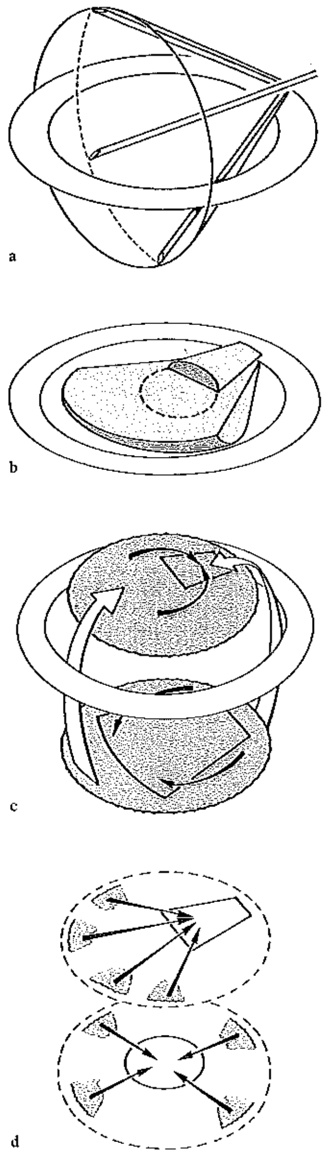

Fig. 8.73. Basic maneuvers for phacoemulsification

a Movements of the emulsifier: The theoretical range of action of the phacoemulsifier is a cone whose apex lies at the access opening.

b Safe regions for movements of the emulsifier. The practical range of action is limited by anatomic constraints (distance from surrounding tissues). There is a large difference, moreover, between the ranges of action in the anterior and posterior chambers since different emulsification techniques are used in each chamber. In the *anterior chamber*, emulsification is done by occlusion and the safety zone is small. In the *posterior chamber*, emulsification can be done in flow, so the safety zone is larger. Only a small fraction of this zone is safe for emulsification by occlusion (circular area at the center of the posterior chamber).

c Movements of the nucleus. To bring the material into the safety zone for emulsification in each chamber, the nucleus is rotated about its axis (*small arrows*). To bring it from the posterior into the anterior chamber, either the inferior or superior pole is elevated (*large arrows*).

d Movements of nuclear fragments. Small fragments are brought to the safety zones of emulsification by transposing them centripetally with aspiration by occlusion.
Above: Anterior chamber
Below: Posterior chamber

Practical Conduct of Phacoemulsification

Insertion of the Emulsifier into the Anterior Chamber

During *insertion* of the instrument into the anterior chamber, the tip is held with its bevel facing downward so that it can glide smoothly along the iris surface. The sleeve is positioned so that its side openings face laterally to ensure that the openings will not snag the wound margins. This also avoids inadvertent fluid injection into corneal parenchyma which might impair transparency or dissect beneath Descemet's membrane.

Following *entry* into the anterior chamber, a lateral position of the sleeve openings prevents tissue displacements that might occur if the openings were positioned vertically.[42] For reasons of spatial tactics, infusion is maintained continuously to compensate for outflow of the cooling stream. Note: In all manipulations with the emulsifier it is necessary to monitor not just the working tip but also its position at the access opening (Fig. 8.69), for that is where space-tactical safety is controlled.

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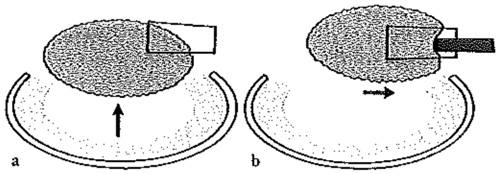
[42] E.g., compensatory tissue shifts (iris prolapse, etc.) in case of a leaking access opening (see Fig. 2.25).

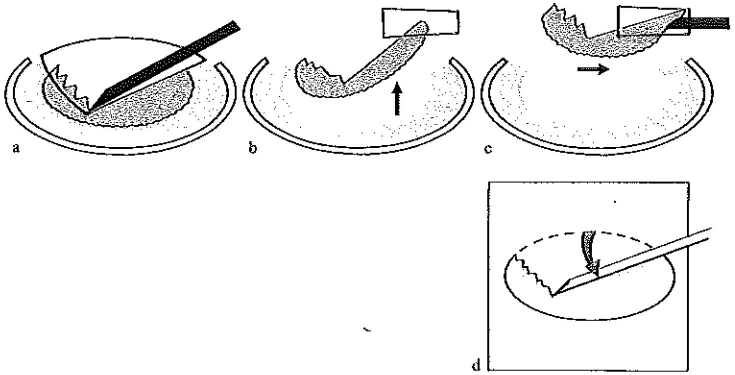


8.74

Fig. 8.74. Basic technique for emulsification in the anterior chamber

a First step: The entire nucleus (peripheral shell and central core) is mobilized and transposed into the anterior chamber toward the safety zone for emulsification.

b Second step: The nucleus is emulsified with aspiration by occlusion within the safety zone of the anterior chamber



8.75

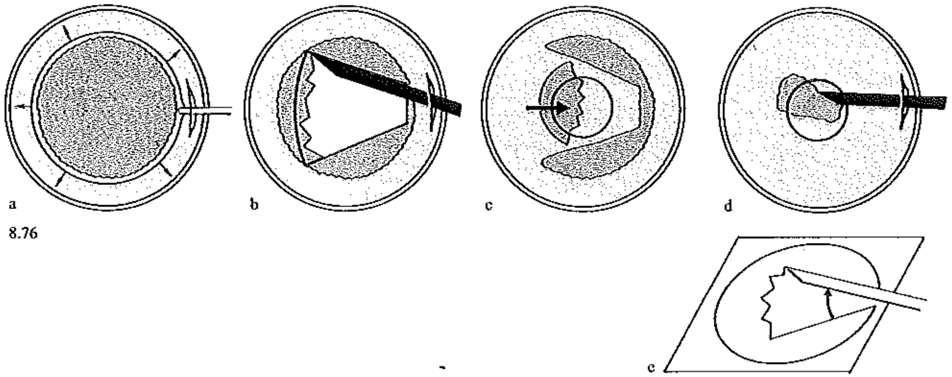
Fig. 8.75. Basic technique for emulsification in both chambers

a First step: The hard central core of the nucleus is emulsified within the safety zone for emulsification in flow.

b Second step: The softer shell is mobilized and transposed into the anterior chamber. The motion vectors have *vertical* components.

c Third step: The remaining nuclear material is emulsified by occlusion within the safety zone of the anterior chamber. All movements of the nucleus are *horizontal*.

d *Note*: Motion of the emulsifier from the empty space toward the tissue to be removed occurs on a *vertical* plane. The bevel of the tip directed toward the empty space faces *upward*



8.76

Fig. 8.76. Basic technique for emulsification within the capsular bag

a First step: Nucleolysis (by hydrodissection).

b Second step: Emulsification of the lens material within the safety zone for emulsification in flow (anterior cortex, anterior nuclear shell, and nuclear core).

c Third step: Transposition of the remaining nuclear shell into the safety zone for emulsification by occlusion at the center of the bag. Note: The vectors of this maneuver are strictly *horizontal*.

d Fourth step: Final emulsification by occlusion (at the center of the bag).

e *Note*: The plane of the movements of the emulsifier is *horizontal*; the bevel faces *laterally* toward empty space

Nucleolysis and Locomotion

Nucleolysis is performed either by hydrodissection or by traction (i.e., combined with locomotion). Depending on the technique selected for phacoemulsification, the entire nucleus, the shell only, or small fragments are transposed into the safety zone for definitive emulsification by occlusion. The motor for **locomotion** consists of pressure or traction. For *pressure*, the necessary gradient between the vitreous chamber and anterior chamber is produced by interrupting the infusion stream. The diaphragm is allowed to bulge forward, pushing the nucleus toward the anterior chamber.

Traction is exerted either by pulling the nuclear material with the tip while aspiration is on (i.e., aspiration for grasping and guidance motions for pulling; no ultrasound), or by pushing with a spatula, or with the tip while aspiration is switched off.

Phacoemulsification in the Anterior Chamber

For phacoemulsification in the anterior chamber, the entire nucleus (i.e., the hard central core along with the softer peripheral shell) is transposed into the anterior chamber (Fig. 8.74). Thus, the initial steps are **nucleolysis and locomotion**. For nucleolysis an (irrigating) cystotome can be used as shown in Fig. 8.47. Locomotion is sustained by a pressure difference between the vitreous and anterior chamber produced by an interruption of the infusion stream.

The second step is the **emulsification itself**. At this point the nucleus is free of its anatomic connections with the cortex and is completely mobile. Basically, emulsification in the anterior chamber is performed by occlusion. An emulsifier tip with a blunt shape is selected.

The emulsifier is used at a low power setting to prevent repulsion of the nucleus with consequent loss of occlusion. Short-burst ultrasound application is an important safety factor and helps to reestablish occlusion after each burst.

As long as the nucleus retains sufficient mass, its inertia can be utilized as a stabilizing factor. Small particles are apposed to the emulsifier tip with the aid of a spatula.

All maneuvers used to present successive portions of the nucleus to the emulsifier tip involve movements strictly on the horizontal plane (i.e., lateral displacement or rotation) to protect adjacent tissues. Vertical movements are unnecessary at this stage and are avoided since they would endanger the endothelium and posterior capsule.

There are two basic methods of phacoemulsification in the anterior chamber: 1) the nucleus is emulsified from the inside outward, i.e., the hard core is attacked first, and the softer peripheral shell is left for

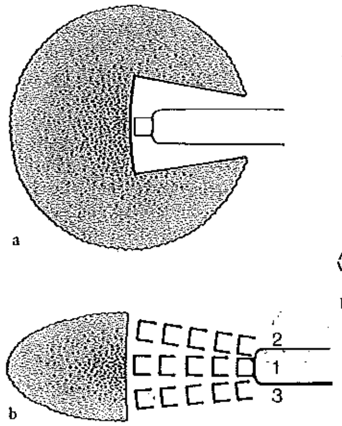


Fig. 8.77. **Methods of emulsification in the anterior chamber: Start of the emulsification**

a First the material within the safety zone is emulsified.

b Steps of the emulsification. The first step (*1*) is emulsification at the equator (see Fig. 8.78a). The second step (*2*) emulsifies the surface and provides exposure for the third step (*3*), deep emulsification

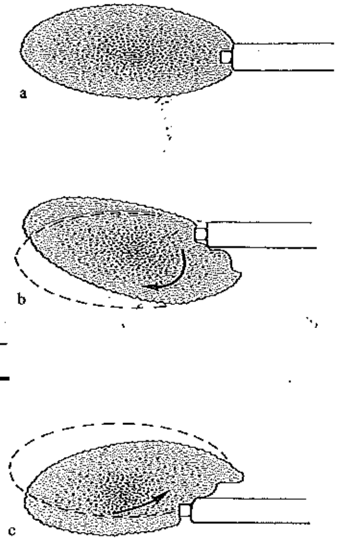


Fig. 8.78. **Emulsification of a mobile nucleus**

a If emulsification is started precisely at the equator of the nucleus, the instrument is aligned perpendicular to the surface. The resistances about the sleeve are symmetrical, and the tip penetrates horizontally into the nucleus.

b, c If the tip is applied above (**b**) or below (**c**) the equator, motion of the nucleus is checked on one side by the sleeve, causing the nucleus to tilt upward or downward

emulsification by occlusion in the final phase, or 2) the nucleus is emulsified from the outside toward the center.

In the former method the peripheral part of the nucleus already within the safety zone is emulsified (Figs. 8.77, 8.78) to gain access to the core. Then the core is successively brought into the safety zone by lateral shift (Fig. 8.79) or by rotation (Fig. 8.80). During emulsification of the hard material, the most difficult part of the procedure, the nuclear mass is still large enough for inertia to be an effective stabilizing adjunct. In the final phase the material is soft and is easily emulsified by occlusion.

In the latter method the soft shell of the nucleus is shelved away first (Fig. 8.81). When the tip reaches the core, the nuclear mass has been significantly reduced and its inertia is low. Thus, the method is safe only when the core is soft enough to be emulsified by occlusion.

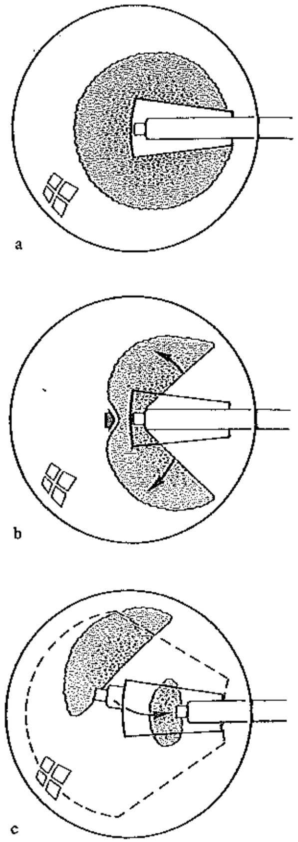


Fig. 8.79. **Methods of emulsification in the anterior chamber: Longitudinal shifting of the nucleus**

a Following the initial excavation (Fig. 8.77), the nucleus is sucked gradually toward the access opening, and emulsification is continued at its center.

b This maneuver is continued until two side fragments remain.

c The remaining fragments are grasped with the suction tip within the wide aspiration zone (*black*) and retracted toward the safety zone (*red*), where the emulsification is completed

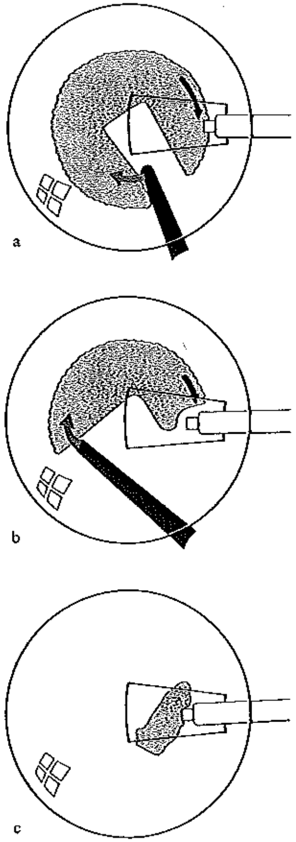


Fig. 8.80. **Methods of emulsification in the anterior chamber: Rotation of the nucleus with a spatula**

a Following the initial excavation (Fig. 8.77), the nucleus is rotated with a spatula (introduced through a second incision) until a new sector enters the safety zone, where it is emulsified.

b As the rotation maneuver is continued, new material is fed to the emulsifying tip, and the nucleus diminishes in size.

c The emulsification is completed as shown in Fig. 8.79

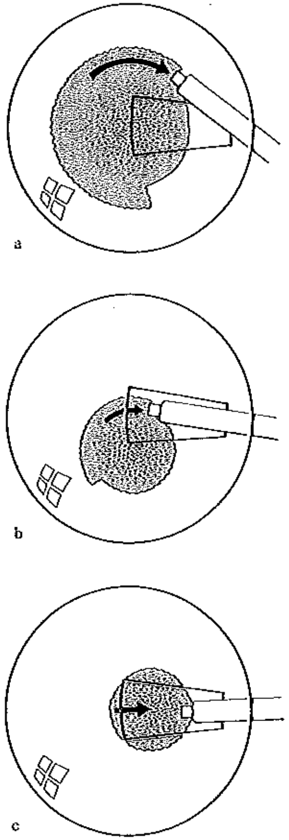


Fig. 8.81. **Methods of emulsification in the anterior chamber: Rotation of the nucleus by aspiration**

a When the tip is applied to the nucleus obliquely on the horizontal plane, the sleeve exerts a checking action which causes the nucleus to rotate as in Fig. 8.78, though here it rotates about a vertical axis. The safety margins in this technique are small for several reasons: First, the tip can easily stray from the safety zone. If, to avoid this, the nucleus is pushed to the center of the anterior chamber, there is a danger that the far edge of the rotating nucleus will scrape against the corneal endothelium. Second, the oblique position of the instrument at the corneoscleral incision can hamper cooling by blocking fluid outflow alongside the tip (see Fig. 1.14e).

b The rotation maneuver is continued. As the nucleus diminishes in size, it can be brought to the center of the anterior chamber for emulsification; the safety margins expand.

c Finally the central core of the nucleus is emulsified

Phacoemulsification in Both Chambers

When phacoemulsification is performed in both chambers,[43] the core and shell of the nucleus are emulsified in different chambers (Fig. 8.75). This allows optimum conditions to be selected for the emulsification of hard and soft material.

The first step is **emulsification of the core of the nucleus in the posterior chamber.** The anatomic connections between the nucleus and cortex are still intact and serve to keep the nucleus immobile. This facilitates the emulsification in flow that is optimal for the hard nuclear core. The material within the safety zone is shelved layer by layer from the surface downward. A sharply beveled tip is used for emulsification in flow (see Fig. 8.66b), and the bevel is directed upward to prevent inadvertent occlusion.

The second step is **nucleolysis and locomotion** of the remaining nuclear shell (i.e., the material outside the safety zone in the posterior chamber) into the anterior chamber. This transfer involves vertically directed vector components. Either the superior or inferior pole of the shell is raised first. The motivating force for lifting the *superior pole* (Fig. 8.82b) is pressure. This is done by interrupting the infusion flow and allowing the nuclear rim to rise. Then for nucleolysis the shell is engaged with the instrument tip and hydrodissected by reactivating the infusion stream. This method is suitable for dense nuclei that differ from the cortex in their compactness (see Fig. 8.46).

The motor for raising the *inferior pole* (Fig. 8.83d) is traction. The material is grasped with the emulsifier tip while the aspiration is on. However, aspiration is safe only for material that can be attacked with the tip opening held horizontally or upwards.[44]

The nuclear rim on the opposite side is first sculpted to make it foldable, then it is pulled toward the entry site of the instrument. Thus, this method is suitable for nuclear material that is soft enough to maintain strong occlusion, i.e., sufficiently strong to withstand the tissue resistance to nucleolysis and folding.

The third step is **emulsification of the nuclear shell in the anterior chamber.** Being soft, the material is emulsified by occlusion. The shell is successively rotated into the safety zone and removed there while the tip is held almost stationary.

Phacoemulsification Within the Capsular Bag

In phacoemulsification within the capsular bag (Fig. 8.76), all maneuvers can be performed through a small capsulotomy. In terms of spatial tactics, then, the capsular bag may be treated as an independent pressure chamber, and its shape can be controlled by adjusting the flow parameters (see Fig. 8.57).

The confinement of all manipulations within a nearly intact bag is the main advantage of this technique, as it reduces the danger to surrounding structures, but it is also a major disadvantage due to the lack of space. The free working space in the capsular bag must be created first by the surgeon. Its greatest extent is available on the horizontal plane. Therefore, all maneuvers are performed in such a way that the instrument and nuclear material are shifted predominantly in horizontal directions.[45] The largest amplitudes for movements of the nucleus are in rotation. In case of a small capsulotomy, these rotational movements must be produced with a single instrument (e.g., with the emulsifier tip) and are not easy to perform (see Fig. 8.47b). They are facilitated by previously separating the connections between the nucleus and cortex.

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[43] Currently this technique is called "emulsification in the posterior chamber" because that is where the procedure is begun.

[44] Pointing the tip backward during aspiration is hazardous to the capsule. Easily deformable material may be sucked abruptly through the large lumen of the aspirating cannula, exposing the posterior capsule to the potentially damaging effect of a large pressure gradient.

[45] Many maneuvers in this technique can be explained simply as a 90° rotation on the vertical plane of manipulation in both chambers (compare Figs. 8.75d and 8.76e!).

The first step, then, is **anterior corticolysis and nucleolysis by hydrodissection.** Hydrodissection is used because there is not enough room to separate the connections by tractional movements. Since hydrodissection is most effective when the reflux resistance is high (see Fig. 8.48b), it is done prior to any further manipulations. The second step is **excavation of the nuclear center** (Fig. 8.84). This is done in two phases: creation of the initial cavity for introduction of the tip, and extension of this cavity throughout the safety zone for emulsification in flow. Occlusion is unavoidable during sculpting of the initial cavity, so short bursts of ultrasound are used at this stage. The bevel of the tip (which is sharp for the emulsification in flow that follows) is directed laterally to avoid unintended aspiration of the anterior or posterior capsule. Subsequent excavation of the nucleus within the safety zone is done in flow. The material in front of the tip remains immobile despite the previous nucleolysis, because the nucleus is well confined within the intact capsular bag. The shelving maneuver is done on the horizontal plane by sweeping the tip laterally from one border of the safety zone to the opposite border. To avoid occlusion, the bevel of the tip faces to the side, toward the cavity already formed. The anterior cortex (previously loosened by corticolysis) is simultaneously removed, allowing visual control of the underlying emulsifier tip.

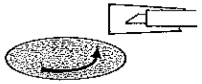
The third step is **locomotion** of the peripheral nuclear shell at the opposite end of the excavation toward the center.

The material is grasped and pulled by aspiration by occlusion. To prepare this step the peripheral shell is cut into occludability, that is, into a triangular shape able to occlude a sharp beveled tip held laterally (see Fig. 8.84b).

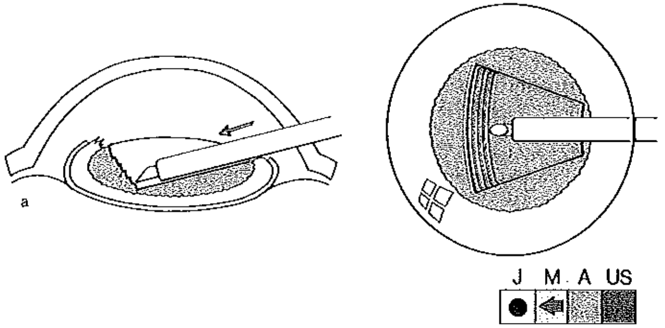
The fourth step is the **final emulsification** of the fragments within the safety zone for emulsification by occlusion at the center of the bag. The infusion pressure and outflow opening are closely monitored and controlled to maintain the shape of the emptying bag; short-burst technique prevents collapse of the bag when the emulsification is completed.

Subsequently the residual shell is rotated until new portions become accessible to the tip; then the steps of emulsification are repeated.

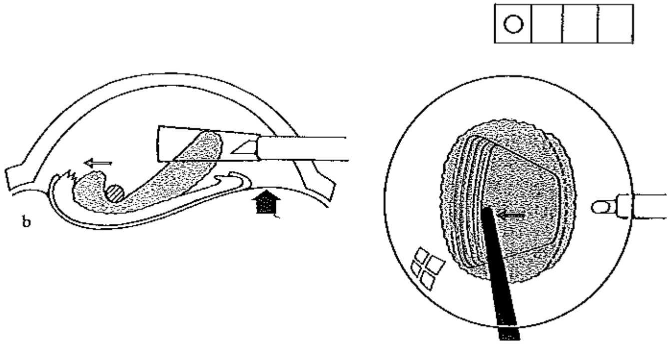
Fig. 8.82. Methods of emulsification in both chambers: Raising the *superior* pole of the nucleus. The diagrams of the footswitch positions show position 1 (infusion only) in the left square (*J*) with a black circle (on) or white circle (off).[46]
Following initial emulsification in the safety zone of the posterior chamber, the *superior* pole of the nucleus is moved into the safety zone of the anterior chamber. In this technique the nucleus must be hard enough to offer adequate resistance to a spatula.



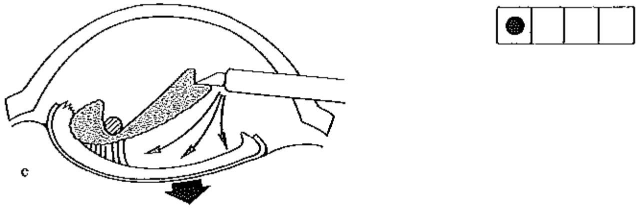
a *Initial excavation*: First the center of the nucleus is emulsified within the capsular bag, leaving a solid "step" on the opposite side (aspiration in flow).



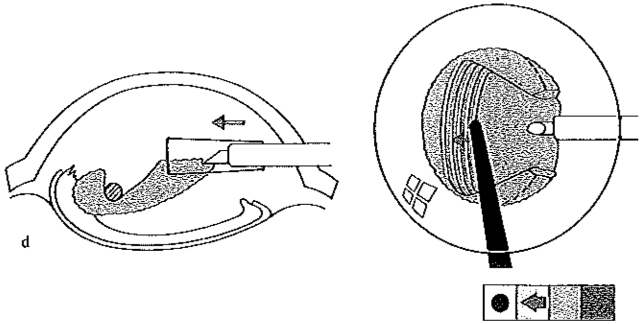
b *Locomotion*: The step is engaged with a spatula, which shifts the nucleus *horizontally* toward the inferior pole until its superior pole appears at the pupil margin. Then the spatula is held steady while the emulsifier is withdrawn toward the access opening to make room for ascension of the superior pole. The superior pole is driven upward by lowering the pressure in the anterior chamber (discontinuing infusion, footswitch position 0) until the diaphragm bulges forward.



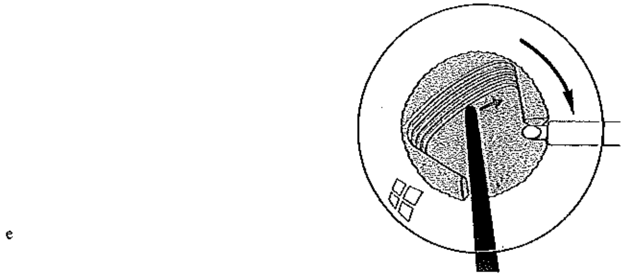
c *Nucleolysis*: The superior pole presents to the tip and is engaged, then the infusion is restarted to induce recession of the diaphragm. The nucleus is now separated from the cortex by hydrodissection; sufficient time must be allowed (in footswitch position 1) for this separation to occur. Then the tip is withdrawn slightly so that the nucleus can fall back again. Nucleolysis is completed by rotation of the nucleus with a spatula (see also Fig. 8.47b).



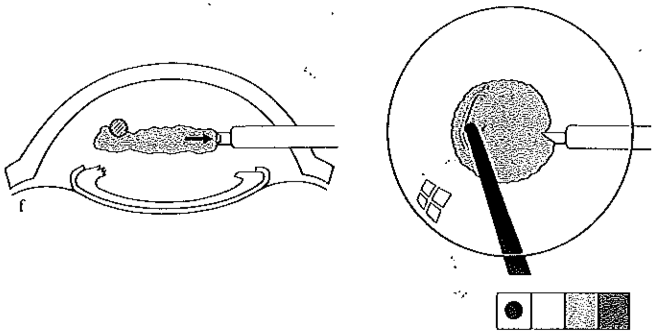
d *Emulsification of the nuclear rim*: The mobilized material of the superior nuclear rim is shifted from the posterior chamber into the safety zone of the anterior chamber by repeating the maneuver in Fig. b. Then the material is emulsified in flow.



e The entire rim is shelved away by bringing new portions to the emulsifier tip. This is done by rotation with the spatula and by lifting with the maneuver in Fig. b.



f *Emulsification of the posterior shell*: Finally the flat, rimless posterior shell of the nucleus is moved to the anterior chamber through aspiration by occlusion. There it is (stabilized with a spatula if necessary) emulsified by occlusion. *Note*: To avoid improper alignment of the shell on occlusion, the bevel of the emulsifier is directed laterally now



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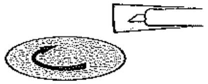
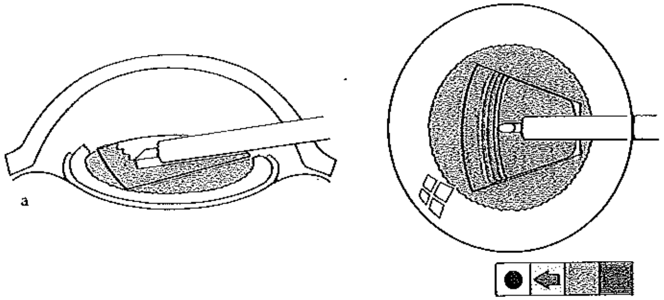
[46] Position 1 was not drawn in the previous figures, because infusion was on during the entire procedure.

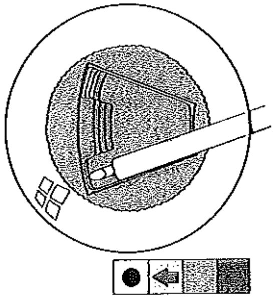
Fig. 8.83. Methods of emulsification in both chambers: Raising the *inferior* pole of the nucleus. Following initial emulsification in the safety zone of the posterior chamber, the *inferior* pole is drawn into the anterior chamber. This method is best suited for nuclei soft enough to be folded after partial excavation.



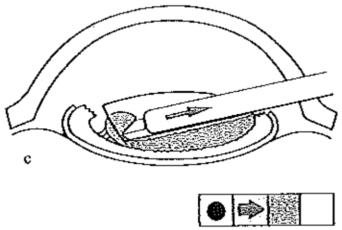
a *Initial excavation*: The nucleus is excavated in the posterior chamber by aspiration in flow to the extent the safety zone allows.



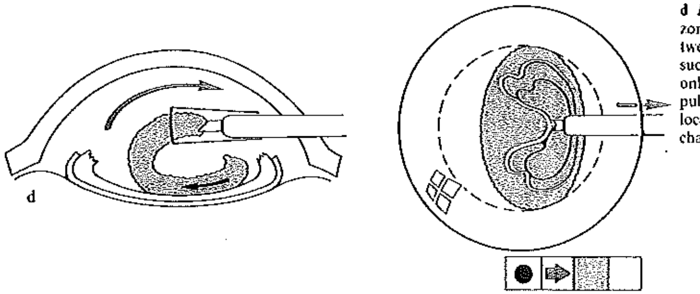
b *Preparation for folding maneuver*: On the far side of the excavation, grooves are cut toward the periphery at both lateral ends so that the intervening border of the nucleus can be folded more easily. These grooves extend beyond the safety zone. Thus the nuclear material is first grasped with suction[47] and then is pulled toward the safety zone for emulsification.



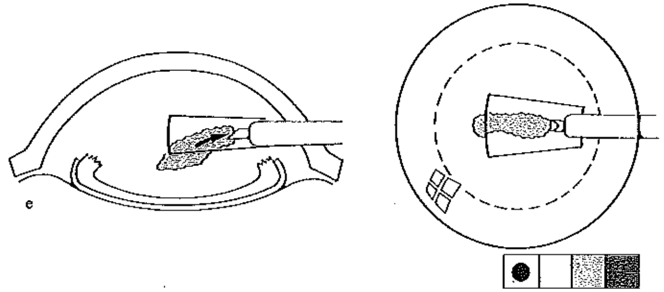
c Now the tip is kept immobile, and the groove is cut by a short burst of ultrasound (emulsification by occlusion).



d *Raising the inferior pole* into the safety zone of the anterior chamber: The rim between the grooves is now grasped with suction (footswitch position 2: Aspiration only, no vibration), folded upward, and pulled toward the access opening. This dislocates the nuclear shell into the anterior chamber.



e *Removal of the nucleus* is completed within the safety zone of the anterior chamber (aspiration by occlusion)



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[47] Remember that the safety zone for aspiration alone (*black outline*) is larger (see Fig. 8.72).

Fig. 8.84. **Phacoemulsification in the capsular bag.** The basic steps in the procedure are the removal of the nuclear core within the safety zone for emulsification in flow, and removal of the portion of the shell opposite the capsulotomy. Subsequently the nucleus is rotated, and other parts are made accessible to the emulsifier.

a–j Sequence of manipulations.
v–z The results obtained after each step.

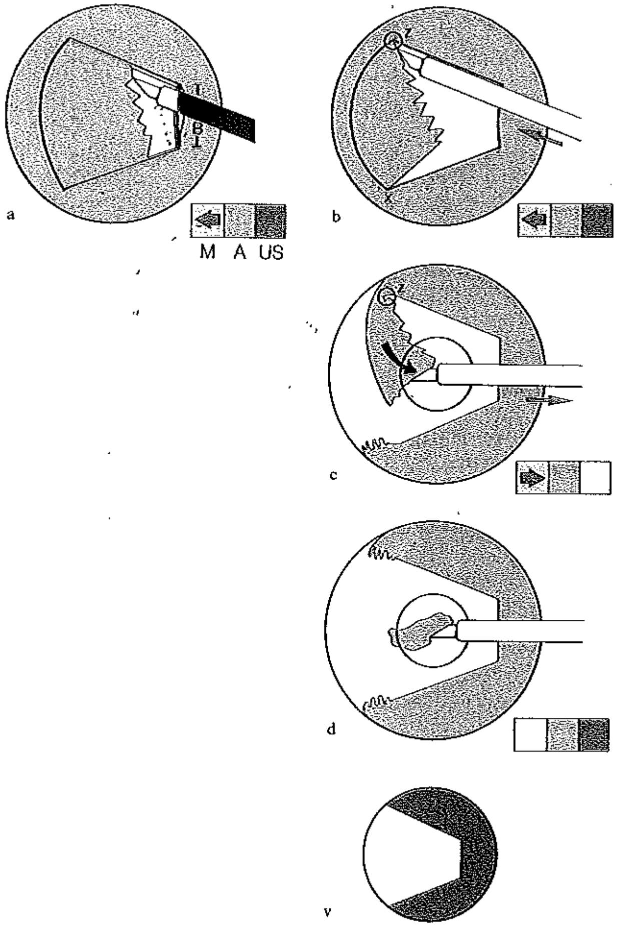
a *Sculpting the initial cavity*: The emulsifier is introduced into the lens through a small capsulotomy whose width depends on the planned arc through which the tip will be swept (i.e., the base B of the safety zone for emulsification in flow). A flat-beveled tip is chosen to minimize the risk of unintended occlusion (see Fig. 8.66b). The bevel faces laterally toward the space already excavated.

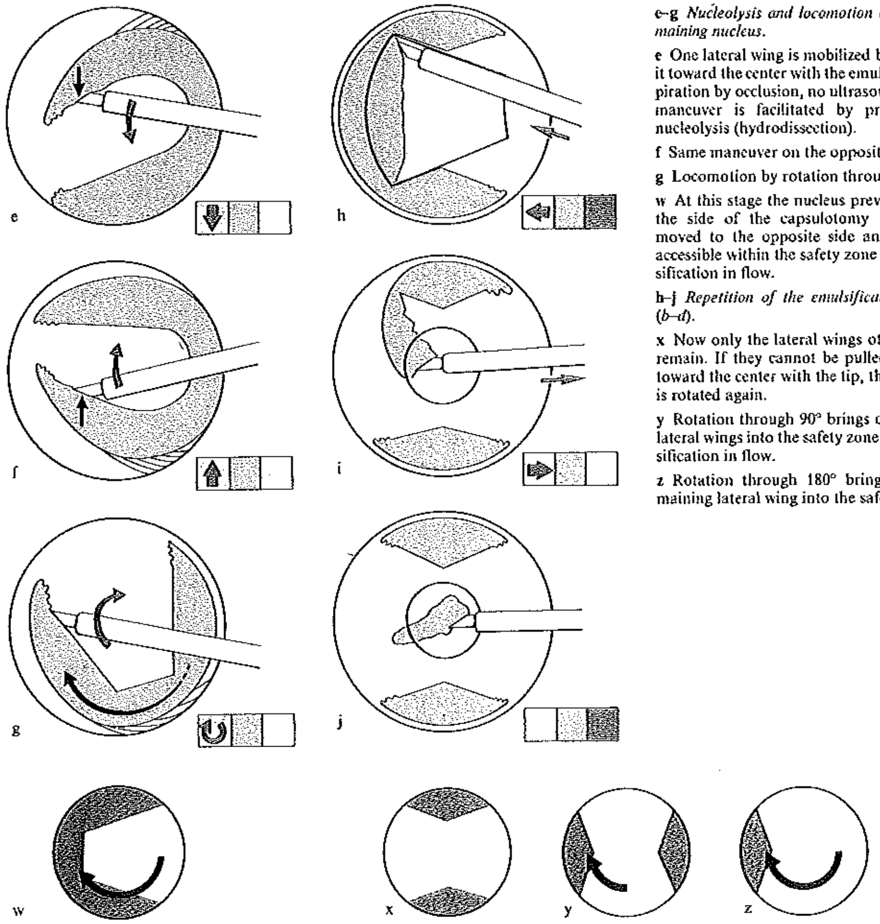
b *Excavation of the nuclear core* by emulsification in flow. With the bevel facing laterally, the cavity is extended by swiveling the emulsifier horizontally. On the side opposite the capsulotomy, a triangular wedge is left in the nuclear shell to serve as a "handle" for pulling it toward the center. The triangle is not isosceles: One side (toward x) is made shorter and steeper than the other to allow for solid occlusion by the beveled tip; the other side, longer and flatter, can easily pivot about point Z at its end.

c *Mobilization of the wedge*. The steep part of the triangle is grasped by occlusion with the aspirating tip (no vibration) and is pulled centripetally.

d The wedge is emulsified by occlusion at the center of the bag.

v Result of **a–d**: Removal of nuclear material in the safety zone and adjoining shell.





e–g *Nucleolysis and locomotion of the remaining nucleus.*

e One lateral wing is mobilized by pulling it toward the center with the emulsifier (aspiration by occlusion, no ultrasound). The maneuver is facilitated by preliminary nucleolysis (hydrodissection).

f Same maneuver on the opposite wing.

g Locomotion by rotation through 180°.

w At this stage the nucleus previously on the side of the capsulotomy has been moved to the opposite side and now is accessible within the safety zone for emulsification in flow.

h–j *Repetition of the emulsification steps (b–d).*

x Now only the lateral wings of the shell remain. If they cannot be pulled directly toward the center with the tip, the nucleus is rotated again.

y Rotation through 90° brings one of the lateral wings into the safety zone for emulsification in flow.

z Rotation through 180° brings the remaining lateral wing into the safety zone

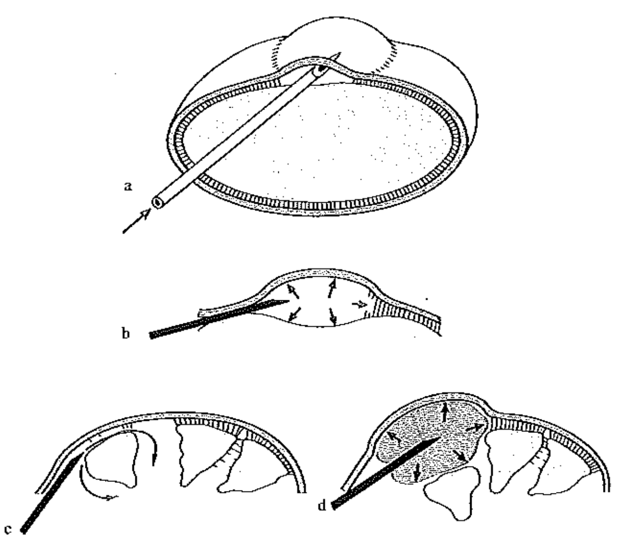


Fig. 8.85. **Corticolysis by hydrodissection**

a Fluid injected beneath the capsule produces a pressure chamber whose expansion separates the capsule from the cortex (see also Fig. 8.49b).

b Only large and compact fragments offer sufficient backflow resistance to allow a pressure chamber to be formed.

c With smaller fragments, resistances to the reflux and spread of watery fluid are too low, so a pressure chamber is not formed.

d Viscoelastic material provides its own flow resistance and thus can separate even small cortical fragments from the capsule (see Fig. 2.19)

8.3.4 Delivery of the Cortex

The cortex of the lens has a soft consistency. Applied forces tend to rupture the cortex and break it up into fragments. As this makes it difficult to manipulate the cortex as a whole, the cortex is removed *piecemeal*. Differences in the size and compactness of the cortical fragments will necessitate the use of various delivery techniques.

Mobilization of the Cortex (Corticolysis)

The cortex is separated from the lens capsule on a preexisting *anatomic cleavage plane*, which can be developed by pressure or traction.

Pressure is applied by injecting fluid into the interspace between the cortex and capsule to create a *pressure chamber* (Fig. 8.85a, b). The advantage of corticolysis by hydrodissection is that it does not affect the suspension of the lens and therefore is safe even when the capsule or zonule is weak.

Similar considerations apply to corticolysis by hydrodissection as to nucleolysis as far as resistances to forward flow and reflux of the fluid are concerned. These resistances can be produced only by injecting the fluid *prior to* removal of the nucleus. If corticolysis by hydrodissection is attempted *after* delivery of the nucleus, it is not only more difficult to inject the fluid precisely between the capsule and cortex, but the corticolysis also becomes much less effective. In this situation hydrodissection can at best mobilize large, compact fragments (Fig. 8.85b). Small cortical remnants, on the other hand, are poorly mobilized because watery fluid tends to flow around them (Fig. 8.85c). However, corticolysis of small fragments can still be accomplished by the use of *viscoelastic material* (Fig. 8.85d).

In mobilization by **traction**, the cleavage plane is torn open by applying tension to the cortex on one side and to the capsule on the other. *Tension on the cortex* is produced by guidance motions with a grasping instrument, the cortex itself acting as an instrument for transmitting the applied tensile forces to the cleavage zone (Fig. 8.86).[48] *Countertension on the capsule* is produced by tension on the zonule. Actually there is a traction chain comprising the instrument, cortex, capsule, zonule, ciliary body and sclera, and the weakest "link" in this chain will give way when traction is applied.

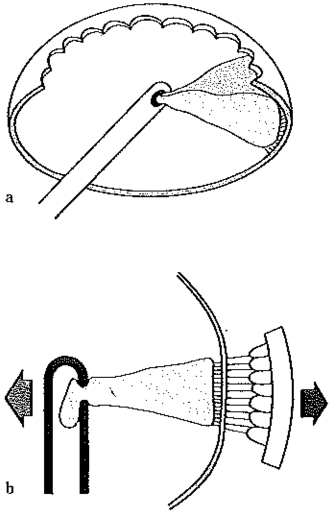


Fig. 8.86. **Corticolysis by traction**

a Cortex is fixed to the cannula by suction and stripped away by traction on the cannula.

b The traction chain encompasses the instrument (and its fixation to the cortex), the cortex, the corticocapsular attachments (the intended cleavage zone), the capsule, the zonule, the ciliary body, and the sclera

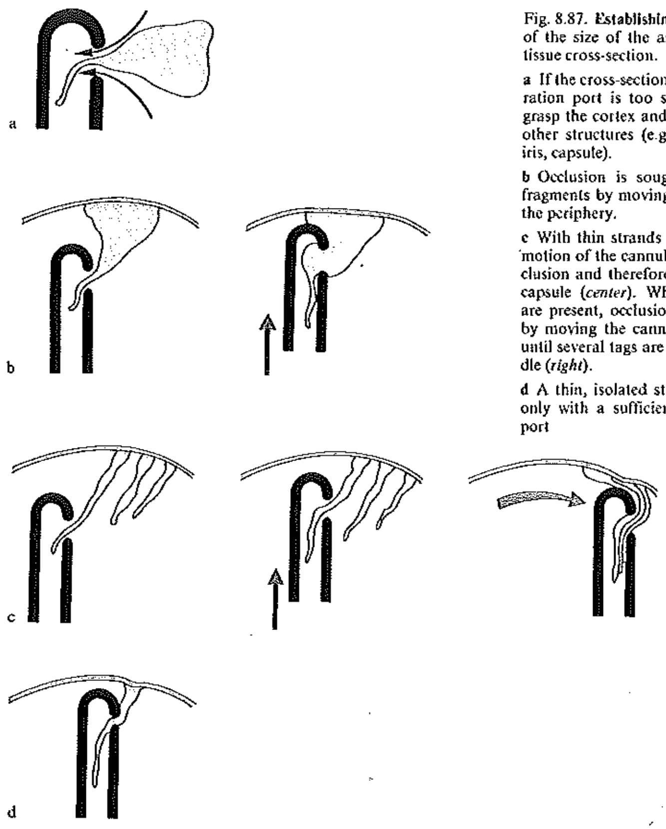


Fig. 8.87. **Establishing occlusion.** Relation of the size of the aspiration port to the tissue cross-section.

a If the cross-section of cortex in the aspiration port is too small, the tip cannot grasp the cortex and will tend to aspirate other structures (e.g., chamber contents, iris, capsule).

b Occlusion is sought in large cortical fragments by moving the cannula toward the periphery.

c With thin strands of cortex, peripheral motion of the cannula cannot provide occlusion and therefore risks aspirating the capsule (*center*). When multiple strands are present, occlusion can be established by moving the cannula circumferentially until several tags are gathered into a bundle (*right*).

d A thin, isolated strand can be grasped only with a sufficiently small aspiration port

Thus, the technique of corticolysis by traction aims at concentrating the effect of the forces on the corticocapsular attachments.[49]

For **grasping** of the cortex, *aspiration cannulas* are used which fixate the material by occlusion. The surgeon's task is first to establish the occlusion and then maintain it while applying traction to the cortex.

The **size of the aspiration port** should conform to the size of the particle to be grasped. If the opening is too small, the cannula cannot grasp enough tissue to transmit forces to the corticocapsular interface; if too large, occlusion is not obtained (Fig. 8.87a). If the rela-

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[48] For the cortex to function in this capacity, it must not be transsected at the grasping instrument. Thus, suction cutters are not suitable *traction* instruments for corticolysis from the capsule fornix. They are used as *cutting* instruments in lensectomy for the removal of the whole lens (including the capsule) and the anterior vitreous.

[49] This is difficult in the presence of a torn capsule, weakened zonule (subluxated lens) or cyclodialysis. If the sclera gives way, it can be reinforced by attaching a stabilizing ring (see Fig. 1.47).

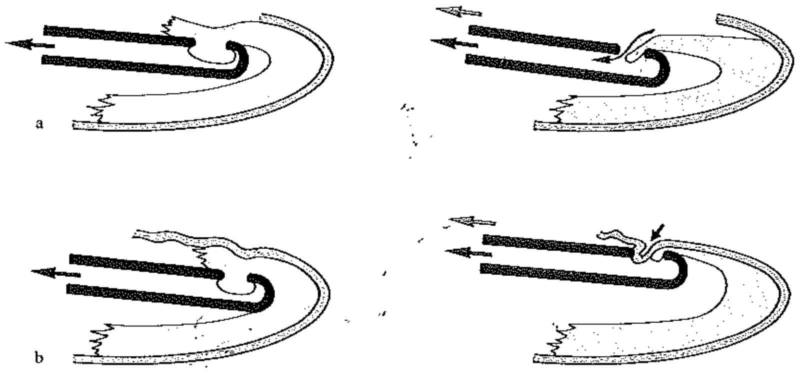

Fig. 8.88. Achieving occlusion by a cannula with an upward-directed side opening
Left: Establishing occlusion
Right: Loss of occlusion during guidance movements

a Here the capsule margin terminates peripheral to the remaining cortex, and the suction tip grasps the cortex outside the capsule area (*left*). If occlusion is deficient, chamber fluid will be aspirated. When traction is exerted on the cortex (*right*), the suction tip moves away from the capsule margin and poses no danger to it.

b Here the capsule margin extends farther centrally than the residual cortex, and the cortex is grasped beneath the capsule (*left*). If occlusion is deficient, the suction tip will seize capsular tissue. The capsule may remain in the danger zone even while traction is applied to the cortex[53]

tion of the cannula opening to particle size is unfavorable, the surgeon can *reposition the cannula* in an attempt to locate a site where occlusion can be established. The cannula is moved to a position where there is more accessible cortex – peripherally for large particles (Fig. 8.87b) and parallel to the capsule sinus for thin strands (Fig. 8.87c). A cannula with a very *small opening* may be needed to grasp tiny individual fibers (Fig. 8.87d).

The **choice of the direction** of the aspiration port depends basically on the *location* of the particle to be aspirated. However, it is also important to consider the effects that would occur if the occlusion were primarily deficient[50] or became so during the corticolysis.[51] To avoid inadvertent aspiration of adjoining vital structures,[52] it is safest to keep the cannula opening pointed in a direction where only additional cortex can be aspirated, i.e., laterally (Fig. 8.89). It is relatively safe to direct the opening toward large aqueous-filled spaces. It is less safe to direct the opening toward the anterior capsule remnants, the capsular sinus, or the posterior capsule, since a break of occlusion in these cases would endanger the capsule and zonule (Figs. 8.88–8.91).

The actual cleavage mechanism, **traction**, is produced either by *suction* or by *guidance motions* of the aspiration cannula. This traction is resisted by the tissue attachments that must be ruptured in the corticolysis, i.e., by the interconnections among the cortical fibers (*intracortical resistance*) and the connections between the cortex and capsule (*corticocapsular resistance*). If these resistances are too high, the occlusion will break and traction will be lost.

It is useful, then, to distinguish between cortex whose attachments are so firm that the slightest motion of the aspiration cannula will disrupt the occlusion ("*firm cortex*") and cortex that will follow motions of the cannula and peel away from the capsule ("*peelable cortex*") (Fig. 8.92).

When dealing with a **firm cortex**, the only way to maintain the necessary occlusion is to hold the aspiration cannula *steady* against the cor-

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[50] The quality of occlusion cannot be controlled if the occlusion is attempted under conditions of poor visibility.

[51] Occlusion may be lost during cortical traction if the resistance to corticolysis is too high. A sudden break of occlusion may also occur when material held by the cannula is suddenly sucked into the opening and aspirated through the lumen.

[52] Recall that the full pressure differential between the initial and terminal pressures becomes active the moment occlusion is lost.

[53] Aspiration with an upward-directed cannula orifice may be dangerous when attempted under conditions of poor vision, for then it cannot be determined whether cortex (*left*) or capsule (*right*) presents to the opening.

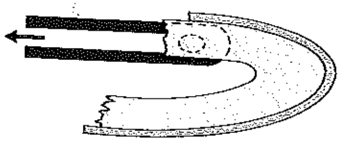

Fig. 8.89. Achieving occlusion by a cannula with a laterally directed side opening. If occlusion becomes deficient, adjacent cortical matter is seized by the suction tip and occlusion reestablished. There is little danger of aspirating the capsule

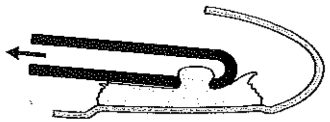

Fig. 8.90. Achieving occlusion by a cannula with a downward-directed side opening. The main danger here is aspiration of the posterior capsule. With its opening turned downward, the cannula should be used only for grasping particles that guarantee occlusion throughout the procedure, e.g., solid cortical fragments whose firm consistency keeps them from being sucked through the opening right away

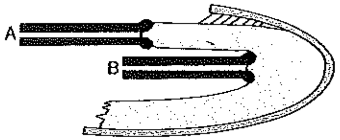

Fig. 8.91. Achieving occlusion by a cannula with a forward-directed opening. Here the side-effects of deficient occlusion depend on the level at which the suction tip grasps the cortex. If the cortex is grasped beneath the anterior capsule (*A*), the suction is directed parallel to the capsule and poses no danger to it. If occlusion is deficient, the tube will simply aspirate more cortex.[54] If the cortex is grasped in the capsular sinus region (*B*), deficient occlusion would allow aspiration of the equatorial capsule with a risk of zonule rupture

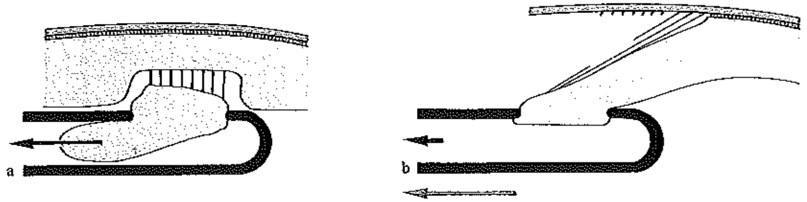

Fig. 8.92. Traction on the cortex

a Firm cortex: The intracortical and corticocapsular attachments are stronger than the occlusion. Since occlusion is lost when the cannula is moved, the cannula must be pressed against the cortex and held stationary. Traction is effected entirely on *aspiration*.

b Peelable cortex: The occlusion is stronger than the cortical resistance. Aspiration serves only to maintain the occlusion, and traction is exerted by *moving* the cannula

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[54] This is true only if the tip is actually beneath a tense capsule. If there are loose, floating capsule remnants ahead, they might be seized inadvertently by the tip.

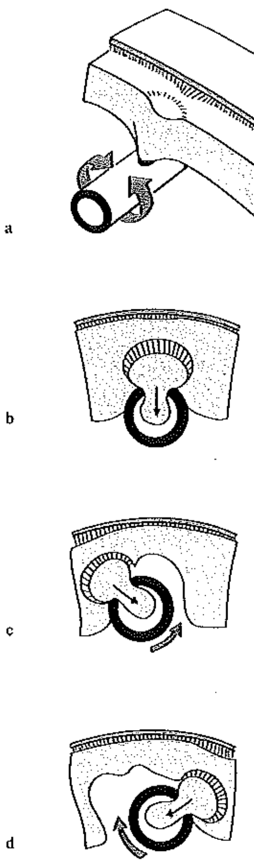

Fig. 8.93. **Removal of firm cortex**

a, b The aspiration port is pressed tightly against the cortex to secure occlusion. The cannula is held stationary during aspiration.

c, d To maintain occlusion during the procedure, the cannula is simply rotated to appose the aspiration port to new portions of the cortex

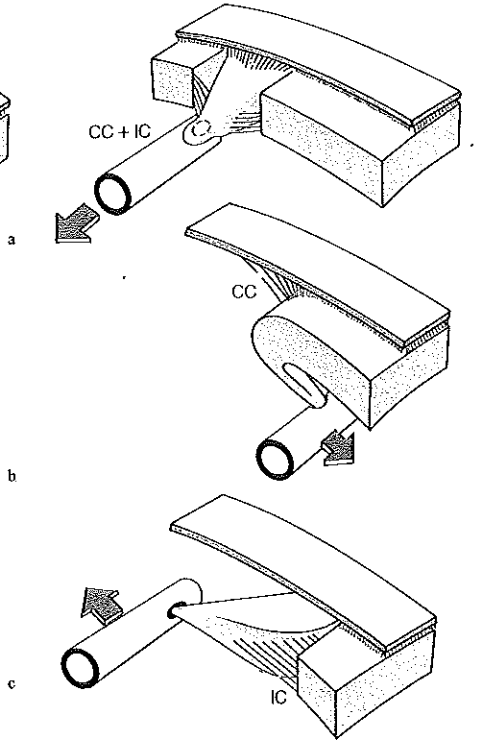

Fig. 8.94. **Removal of peelable cortex**
CC corticocapsular attachments
IC intracortical attachments

a Making the initial gap. At this stage the intracortical attachments are intact and active on both sides of the particle to be grasped. Tension on the intracortical and corticocapsular attachments is diffuse. If these resistances are too high the initial gap is produced by aspiration alone (according to the technique shown for firm cortex in Fig. 8.93).

b The initial gap having been formed, the intracortical attachments are intact on only one side of the particle to be removed. As the corticolysis proceeds, the goal is to place tension on the corticocapsular and intracortical attachments separately rather than jointly so that the total resistance to the traction is reduced. By applying *circumferential traction away from the initial gap*, tension can be placed selectively on the corticocapsular attachments below the anterior capsule.

c Following separation of the corticocapsular attachments below the anterior capsule, the intracortical attachments are ruptured by applying *circumferential traction toward the initial gap*

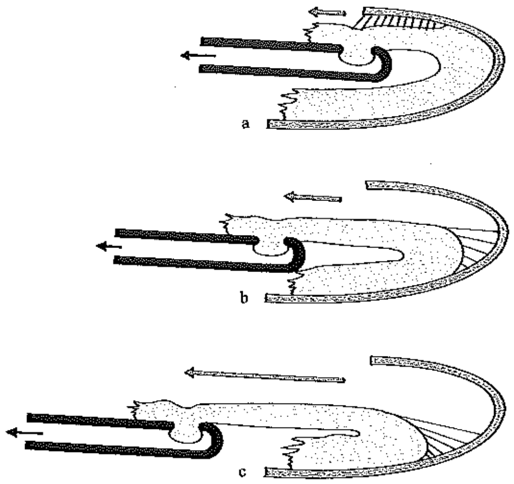

Fig. 8.95. **Removal of peelable cortex.** Resistances encountered by centripetal traction. Initiating traction below the anterior capsule.

a Traction on cortex below the anterior capsule places a diffuse tension on the corticocapsular attachments.

b When the sinus is reached, tension becomes selective, and resistance to separation is decreased.

c As the cortex is stripped from the posterior capsule, tension becomes even more selective and resistance minimal

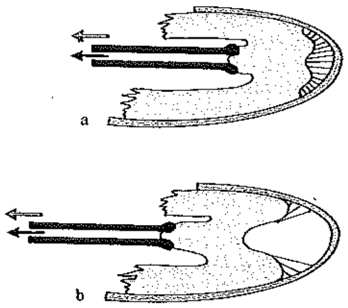

Fig. 8.96. **Removal of peelable cortex.** Initiating centripetal traction in the sinus.

a If traction is initiated in the capsule sinus, the tension is diffuse and the resistance to separation is high (danger of transmission to the zonules).

b As the traction is continued, selective tension is exerted on the corticocapsular attachments at both the anterior and posterior capsule

tex and rely entirely on suction to effect the corticolysis.[55]

Traction on a **peelable cortex**, on the other hand, is produced by *guidance motions* of the aspiration cannula (Fig. 8.92b). Occlusion is maintained by moving the cannula in directions where the lowest resistances are encountered, i.e., in directions that stress the *intracortical* and *corticocapsular* attachments separately and selectively (see Fig. 2.55c). The highest resistances are encountered during formation of the initial gap, i.e., extraction of the first piece from the intact cortex (Fig. 8.94a). During removal of the remaining strips, the intracortical resistances are reduced by almost half.

When starting corticolysis from the anterior cortex (Fig. 8.95) separation from the *anterior capsule* is the most difficult phase because there the countertension against traction at the cortex is low. In *centripetal movements* the traction is opposed by a diffuse resistance from corticocapsular attachments (Fig. 8.95a), and tension becomes selective only when the dissection has reached the capsular sinus (Fig. 8.95b). Conversely, if corticolysis is initiated at the sinus (Fig. 8.96) tension is diffuse at the sinus and becomes selective at the anterior and posterior capsule.

After an initial gap has been formed, *circumferential motion* of the cannula facilitates separation from the anterior capsule (Fig. 8.94b and c).

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[55] This requires use of a cannula that can both aspirate and remove firm material. Matter too solid for removal in this way must be delivered by the same techniques used for the lens nucleus. The suitability of firm cortex for hydrodissection can be exploited by injecting fluid to weaken the corticocapsular bonds before applying traction to the cortex itself.

Removal of the Cortex

There are three basic methods for removing the mobilized cortex:

1. The cortex is **aspirated** through the lumen of the cannula. This is held stationary at the center of the anterior chamber because that is the least hazardous position in case occlusion is broken (Fig. 8.97d *left*).
2. The particles are flushed from the anterior chamber by **irrigation** (i.e., by positive pressure) (Fig. 8.97d, *center*). The cannula opening is held close to the chamber outlet as a safety precaution in case of compensatory bulging of the diaphragm (see also Fig. 2.24).
3. The particle is withdrawn from the eye while fixed at the cannula tip (i.e., by **guidance motions**). In this method the cannula is passed into and out of the eye for each individual particle (Fig. 8.97d *right*).

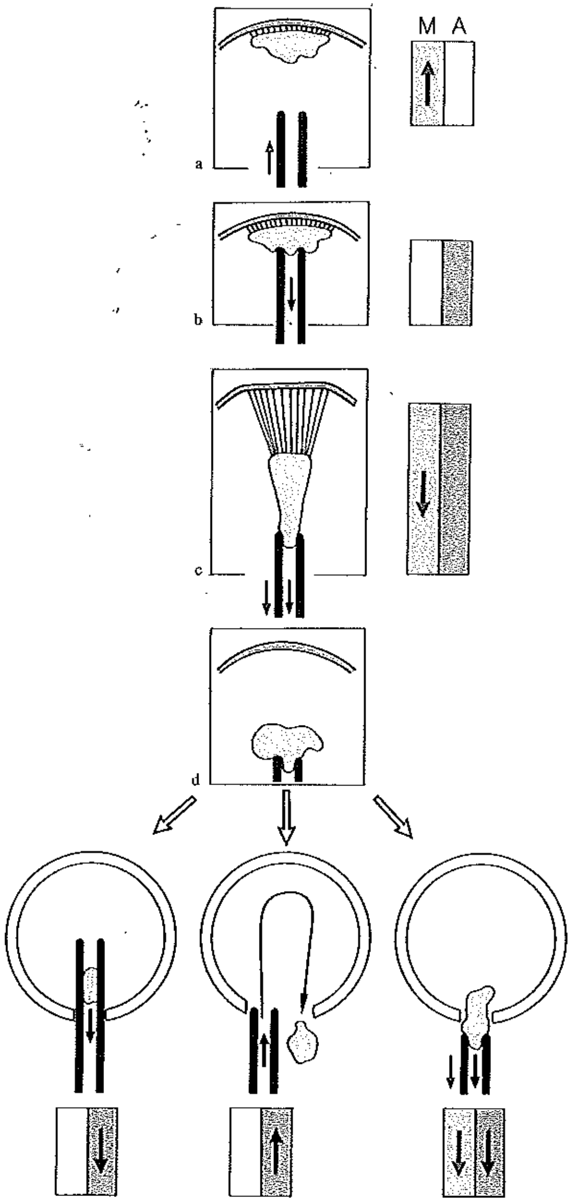

Fig. 8.97. **Phases in delivery of the cortex.** *Bicolor column*: Guidance motions (*M*) and use of aspiration (*A*) in the various phases.

a *Seeking occlusion*: Through guidance motions, the suction tip is applied to the cortical fragment. Aspiration is not switched on until the tip is fully apposed to the fragment.

b *Grasping*: Guidance motions are discontinued, and aspiration is switched on. The cannula is held immobile at this stage so that concomitant motion of the capsule or iris, signifying inadvertent aspiration, can be recognized.

c *Traction*: Guidance motions are resumed while aspiration is maintained.

d *Removal. Left*: The particle is aspirated through the lumen of the cannula itself, which is held stationary.
Center: The particle is removed by irrigation. Motion of the cannula is limited to regulating the cross section of the access opening. *Right*: The particle is retracted from the chamber with the cannula, i.e., by a continuation of phase **c** (guidance motions of the cannula while aspiration is on)

Summary of the Procedure for Delivery of the Cortex

Delivery of the cortex can be divided into four phases based on the forces that are applied (i.e., aspiration and guidance motions, Fig. 8.97):

1. **Seeking occlusion.** Only the cannula is moved. Suction is *not* activated until the cannula opening is seated firmly against the cortex (to prevent aspirating aqueous, iris or lens capsule).
2. **Grasping** (establishing firm occlusion). The grasping force is produced by *activating the suction*. The operator performs *no guidance motions* at this time so that he can detect any concomitant motion of the iris or lens capsule signalizing unintended aspiration.[56] When the operator is certain that the cannula is well occluded by cortex only, he may proceed to the next phase.
3. **Traction.** The grasped cortical matter is torn away from the capsule. *Guidance motions* and *suction* are applied concurrently.
4. **Removal.** Whether the cannula is held stationary in this phase or maneuvered by guidance motions, and whether positive or negative pressure in the cannula is used, depends on the selected mode of transport.

8.3.5 Operations on the Posterior Lens Capsule

The posterior lens capsule is delicate and easily torn. Once a *tear* is initiated, it will spread in response to the slightest force. Directly behind the lens capsule is the *anterior hyaloid*, which is even more vulnerable. Thus, any manipulation of the capsule threatens the integrity of the vitreous body and must be planned with that risk in mind.

Surgical procedures on the posterior capsule are further complicated by the difficulty of *visual control.*[57] Thus the surgeon must rely partly on indirect signs to identify the boundaries of the capsule and its relation to other structures.

Polishing the Posterior Capsule

Polishing is a method for cleaning the posterior capsule of any residual cortical remnants and opacities that are adherent to its anterior surface.

Residual **cortical fibers** *too fine* to occlude the opening of an aspiration cannula are *wiped away* with a blunt instrument (e.g., spatula, irrigation cannula) that is applied directly over or alongside the residual matter. Polishing instruments applied to the *surface* of the fibers need not come in contact with the capsule itself. The instrument grips the particles through *friction*; therefore its working end is finely roughened and has a relatively large surface area (Fig. 8.98a).

By contrast, instruments applied *alongside* the residues must come in contact with the posterior capsule in order to function. They mobilize the particles by blocking their evasion during guidance motions. The instrument must actually press against the capsule, *making it tense*, so that the contact becomes sufficiently strong to prevent particles from slipping underneath. The efficacy of this maneuver depends on the lower *edge* of the instrument, which must appose firmly to the capsule surface (Fig. 8.98b). This necessarily creates force vectors directed toward (perpendicular to)

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[56] Immobility of the tip on grasping is especially important if a small pupil prevents direct visualization of the cannula opening.

[57] The lens capsule is transparent and invisible under coaxial illumination. Also, it is usually too thin to cause scattering sufficient to be seen under oblique illumination.

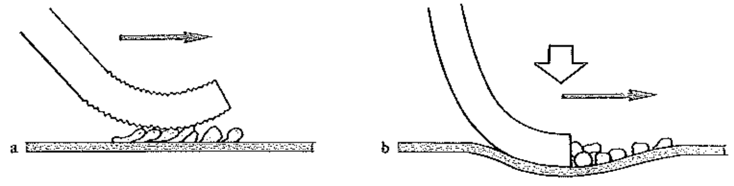

Fig. 8.98. **Polishing the posterior capsule**

a Instrument applied to the *surface* of the cortical residue. Forces are transmitted by friction against the surface of the residual fibers. If the undersurface of the polishing instrument is large and roughened, minimal forces are needed. Once contact is established, the instrument is moved strictly parallel to the lens capsule.

b Instrument applied *alongside* the cortical residue. To function properly, the polishing instrument must appose flush to the capsule surface and must tense the capsule so that the cortical fibers will not push it away from the instrument. This tension implies force vectors directed perpendicularly toward the capsule (*large arrow*). Once adequate tension has been established, the polishing instrument is moved strictly parallel to the capsule surface (*small arrow*)

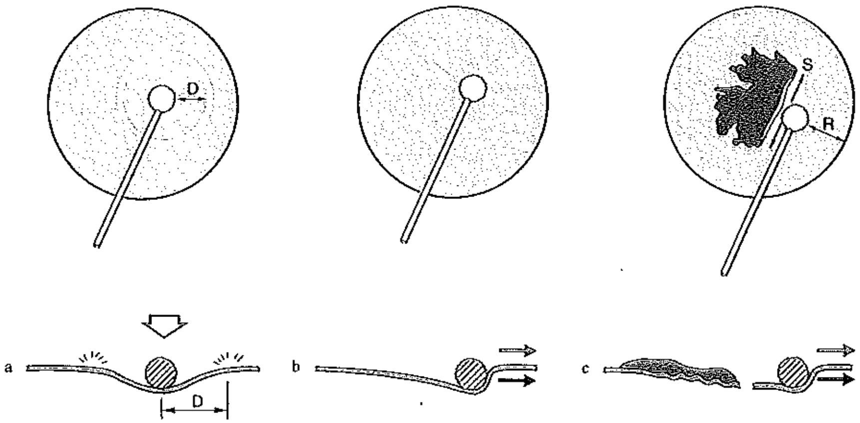

Fig. 8.99. **Visual monitoring of the polishing maneuver**

a By making the capsule tense, the polishing instrument forms an indentation whose borders are made visible by light reflexes. When the reflex appears halo-like, the distance *D* between the edge reflex and instrument indicates the diameter of the indentation and is proportional to its depth. *D* should remain constant as the instrument is moved. This signifies that the instrument is moving freely over the capsule without obstruction, and that a constant capsule tension is being maintained.

b Traction folds signify concomitant motion of the capsule, i.e., that the instrument has "snagged" the capsule and is dragging it. Capsule tension increases on the side of the folds.

c If the capsule is stiffened by a fibrotic plaque, traction folds may not appear, so excessive tension is not easily recognized. The border between the plaque and normal capsule is prone to tearing due to the difference in elasticity. The main risk of rupture exists in motion away from the plaque margin (*R*); motions parallel to the margins of the fibrosis (*S*) are safest

the capsule itself.[58] Since the operator has no appreciable tactile feedback, he must rely on visual criteria when deciding how much force to apply. The forces produce an *indentation* of the capsule, recognizable by a circular edge reflex whose distance from the site of instrument contact indicates the depth of the indentation (Fig. 8.99a).[59]

Once contact has been established, further application of perpendicular forces is suspended, and the polishing instrument is now moved strictly parallel to the capsule surface. Visual control shows a concomitant movement of the edge reflex, whose diameter should remain constant. *Traction folds* (Fig. 8.99b) signify excessive tension of the capsule; they are a warning sign of impending rupture.

Excessive local tension may escape notice at sites where the capsule is indurated by *fibrotic plaques*. The danger of tearing is usually greatest at the plaque margin, where the rigid fibrosis "fixates" the normal, elastic capsule. Polishing at the edge of the plaque is safest with strokes parallel to the margins (Fig. 8.99c).

The **fibrotic plaque** itself is not easily removed. Its *anterior surface* is smooth and is continuous with normal capsule, so it is difficult to engage with an instrument. The *posterior surface* of the plaque is often embedded in folds of the underlying capsule, making it difficult to establish a plane of separation. Moreover, the plaque has a much tougher consistency than the capsule, so any dissecting instrument passed into the interfacial area will have a tendency to deviate toward the less resistant capsule. Consequently, attempts to remove fibrotic plaques entail a *high risk of capsule rupture*.

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[58] The capsule cannot be made tense unless the zonule is intact. Subluxation of the lens or zonule weakness due to pseudoexfoliation can make it impossible to polish the capsule.

[59] A lax capsule (e.g., following removal of a giant nucleus) requires considerable indentation. Visual monitoring then becomes difficult because adequate indentation may move the contact site out of the focus of the microscope, so refocusing is required. Also, the localized "dimple" in the posterior capsule becomes less pronounced, so the circular edge reflex is weak. Hence it is dangerous to use sharp-edged polishing instruments, and a lax capsule is preferably polished with a blunt instrument that touches only the surface of the cortical fibers.

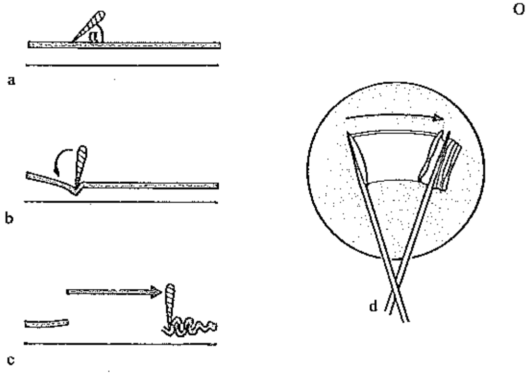

Fig. 8.100. **Posterior capsulotomy by tearing with a discission knife**

a The knife is applied to the capsule at an angle (α) of approximately 45°.

b The blade angle is increased to 90° to optimize friction at the contact site.

c The knife is guided in a sweeping motion parallel to the capsule surface. *Note*: The instrument is used not as a knife but as a "grasping instrument" which tears rather than cuts the capsule.

d Lateral sweeping motion produces tear

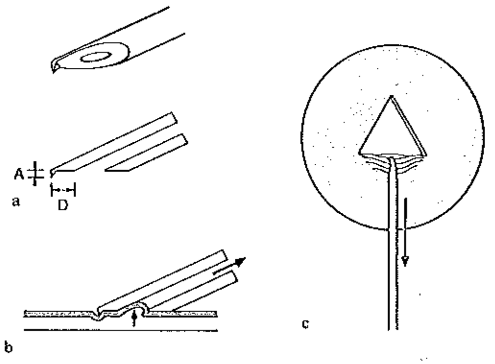

Fig. 8.101. **Posterior capsulotomy using an aspirating cannula with an angled tip**

a The outermost tip of the cannula is bent *toward* the beveled surface to form a hook. The tip should not be longer than the thickness of the capsule (*A*).

b The beveled surface of the cannula is placed against the capsule, sinking the hook into the tissue. Gentle suction aids the fixation of the capsule to the cannula so that the fixating force vectors are directed away from the vitreous rather than toward it. *Note*: If the cannula has a very flat bevel, the distance *D* from the opening to the tip (and thus to the capsulotomy) is large, so the risk of inadvertently aspirating vitreous is decreased.

c Traction on the cannula produces a triangular capsulotomy analogous to Fig. 8.30a

Posterior Capsulotomy

The main difference between anterior and posterior capsulotomy is that the anterior capsule overlies lens matter that may be damaged without compromising the surgical goal, since its removal is already planned. However, the posterior capsule overlies *vitreous*, which must be preserved. Every effort is made, therefore, to direct a minimum of force posteriorly in a planned posterior capsulotomy. *Cutting* with knives or scissors tends to produce force vectors directed toward the vitreous. The safest way to open the posterior capsule surgically is by *tearing*, where applied forces exert a grasping function and separation is directed parallel to the capsule surface.[60]

Because the capsule itself is grasped, *contact* between the instrument and capsule must be stronger than in polishing. *Traction folds* are a positive sign, indicating that the desired effect is being achieved. The contact area between the instrument and capsule should be very small to achieve a maximum concentration of *pressure*. If sharp-edged instruments are used for this purpose, they do not act as cutting instruments but as ultrafine contact spatulas that first grip and then tear the tissue (Fig. 8.100). The "grip" can be improved by suction (Fig. 8.101). Once the capsule is opened, protection of the anterior hyaloid is aided by allowing aqueous or viscoelastic material to flow into and *widen* the interspace (Fig. 8.102).

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[60] The principles governing the application of laser light to the capsule are discussed in Chap. 2.3.

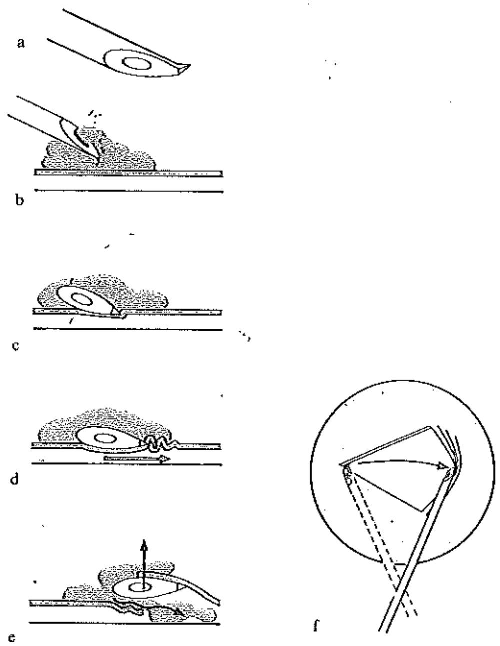


Fig. 8.102. **Posterior capsulotomy using an injecting cannula with an angled tip (injection of viscoelastic material)**

a The tip of an infusion cannula is bent *away* from the beveled surface.

b Viscoelastic material is injected over the proposed capsulotomy site.

c The cannula is placed against the capsule with the tip pointing in the direction the cannula will be moved.

d The cannula is pushed along the capsule surface, raising a tissue fold that is engaged by the sharp tip.

e The cannula is lifted and tears open the capsule. This lifting maneuver creates a suction effect that draws viscoelastic material from the anterior chamber beneath the capsule. Additional viscoelastic material can then be actively injected beneath the capsule to protect the anterior hyaloid.

f The capsulotomy is enlarged by a sweeping motion of the cannula

Management of Incarcerations of the Posterior Lens Capsule

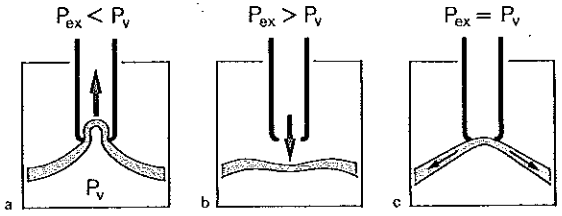
In case of an inadvertent occlusion of the aspiration port by the posterior lens capsule, the fate of the latter depends on the pressure differential between the spaces on both sides of the capsule (Fig. 8.103).

If the suction is on, the pressure in the aspiration system is lower than in the vitreous space, and the lens capsule is sucked into the aspiration port (Fig. 8.103a), where it is apt to be torn.

If the pressure in the aspiration cannula is then raised above the vitreous pressure by a *back-flush* of fluid, the capsule can be repelled (Fig. 8.103b).

If a back-flush system is not incorporated into the aspiration system, the only recourse is to keep the pressure on both sides of the membrane equal and to rely on the intrinsic tension of the capsule for its retraction (Fig. 8.103c). In practice, the pressures in all parts of the hydrodynamic system are brought to atmospheric (=0): In the aspiration system a valve to the outside air is opened. The globe is transformed into a pressureless system (see Fig. 1.3c) by keeping open the access portal and stopping the infusion stream (Fig. 8.104b).

Interrupting the infusion stream for this purpose may seem paradoxical since it may appear that the flow of the infusion is pushing the capsule away from the aspiration cannula. But in fact the infusion raises the pressure within the globe and thus pushes the capsule into the aspiration port (Fig. 8.104a). Only in a pressureless system can the infusion be exploited to repel the capsule, provided short bursts are used which infuse so little volume that no pressure increase can result (Fig. 8.105).



8.103

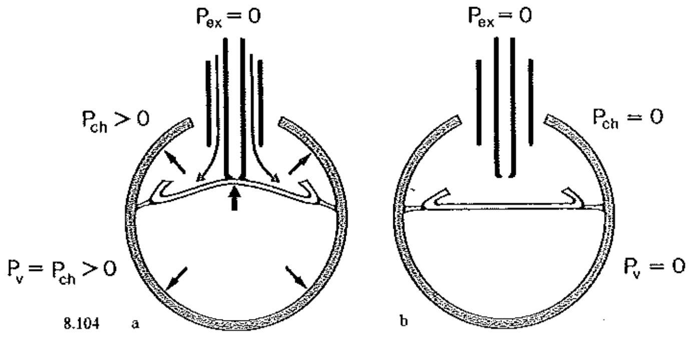
Fig. 8.103. **Effect of pressure differentials on the behaviour of an occluding lens capsule**

P_{ex} outflow pressure
P_{ch} chamber pressure
P_v vitreous pressure

a If the pressure in the precapsular space (aspiration system) is lower than in the retrocapsular space (vitreous chamber), the occluding membrane is sucked into the aspiration port.

b If the pressure in the aspiration system becomes higher (through back-flush), the membrane is pushed back and occlusion no longer exists.

c If the pressures on both sides of the membrane are equal, the tension of the capsule determines whether the frictional resistance between the incarcerated capsule and the aspiration port can be overcome and the capsule released

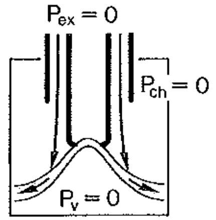


8.104

Fig. 8.104. **Releasing an incarcerated capsule without back-flush**

a If the aspiration is stopped and the pressure in the aspiration system is brought to zero, there will be a pressure differential at the aspiration port if the infusion stream continues and keeps the intraocular pressure above zero

b If the infusion is also stopped, the pressure in the globe falls to zero (provided the outflow path from the chamber remains open)[61]



8.105

Fig. 8.105. **Retraction of the posterior lens capsule in a pressureless system**

Bursts of infusion so short that they cannot raise the intraocular pressure increase the tension of the capsule and allow for retraction of the membrane

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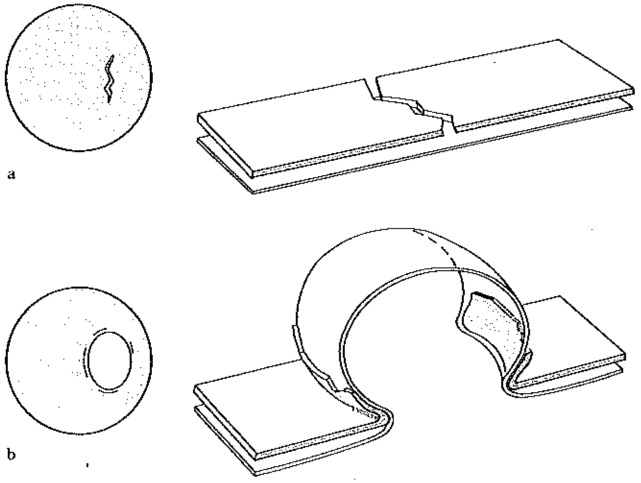
[61] This is true only if the pressure in the vitreous chamber is zero. If there is positive vitreous pressure, only the pressure in the anterior chamber becomes zero. There remains a pressure differential at the aspiration port, and there is no way to repel the incarcerated capsule (unless one succeeds in providing a back-flush with pressures above those in the vitreous).



8.106

Management of Posterior Capsule Rupture

All measures following rupture of the posterior capsule are geared toward the behavior of the *vitreous*. The goal is to isolate the posterior capsule and anterior segment from the vitreous body.

If the anterior hyaloid remains behind the capsule, the surgery may proceed as for a planned capsulotomy. This uncomplicated situation is recognized by observing the *margins of the tear*, which should retain their original linear or sharply angulated shape (Fig. 8.106a).

If the vitreous moves *forward*, it will separate or even enlarge the capsule tear. The defect in the elastic capsule then becomes circular in shape – a sign that an active force is pushing apart the margins of the tear (Fig. 8.106b).

If the *anterior hyaloid* has remained **intact**, the prolapse can be repositioned and the margins of the posterior capsule reapproximated. Since there is still a boundary between the vitreous chamber and anterior chamber, the problem can be solved by space-tactical means. Raising the anterior chamber pressure to a level exceeding the vitreous pressure will push the prolapse backward. This requires a watertight wound closure.

If the operating plan prohibits definitive closure of the anterior chamber (e.g., prior to the insertion of an IOL), the pressure in the anterior chamber cannot be raised; *fluid* injection has no effect. If *air* is injected in this situation, it functions less as a space-tactical instrument than as an expanding spatula. The bubble presses on the prolapsed vitreous only from above, so it is effective for flattening the prolapse but it will not necessarily reduce it (Fig. 8.107).[62] For reducing a prolapse with *viscoelastic substance*, the material is injected first around the sides of the prolapse to reapproximate the everted margins of the lesion (Fig. 8.108). The viscoelastic ring contains the material that is injected later towards the center in order to direct so that is directed the prolapse back through the capsule lesion.[63] Once the torn margins of the capsule are fully reapproximated, the *reduction* is complete (Fig. 8.106a).

If the *anterior hyaloid* is **ruptured** and the vitreous prolapse is not reducible by the method described, reduction must be accomplished by decreasing the vitreous volume, i.e., by *anterior vitrectomy*.

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[62] The main advantage of having air over a flattened vitreous prolapse is that the bubble defines areas in the anterior chamber that are devoid of vitreous and so are available for surgical manipulations. Note, however, that vitreous may reappear in the anterior chamber following absorption of the air in the postoperative period.

[63] In this final phase of the reduction when only downward-directed forces are needed, air can also be injected over the viscoelastic material. This can be done as soon as the capsular tear has lost its circular shape and its margins have started to move closer together.

Fig. 8.106. Behavior of the breached posterior capsule

a If the anterior hyaloid remains in its anatomic location behind the lens capsule, the capsule lesion will have straight or sharply angled margins.

b If vitreous prolapses through the breached capsule, it will separate the margins of the lesion, which now appears circular due to the interaction between the evenly distributed forces of the protruding vitreous and the evenly distributed resistance of the capsule

Fig. 8.107. Attempt to reposition intact prolapsed vitreous with air

a An injected air bubble compresses the prolapse from above and will reduce it if the anterior chamber is closed and the pressure can rise there[64].

b If the anterior chamber is not completely watertight, expansion of the bubble will cause a compensatory loss of aqueous. The prolapse is flattened but not reduced.

c With a large prolapse, there is insufficient aqueous to compensate for the volume shift, and the expanding bubble will tend to expel vitreous from the eye rather than reduce the prolapse

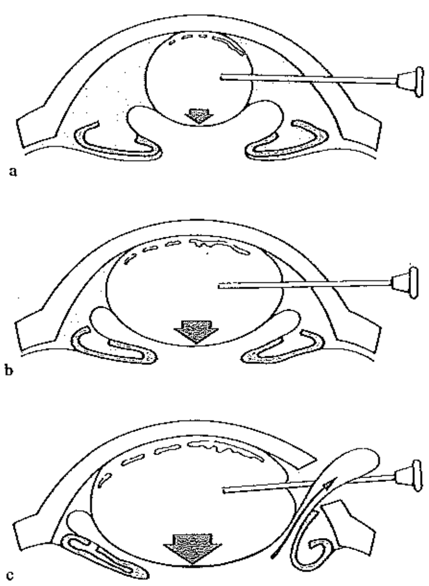
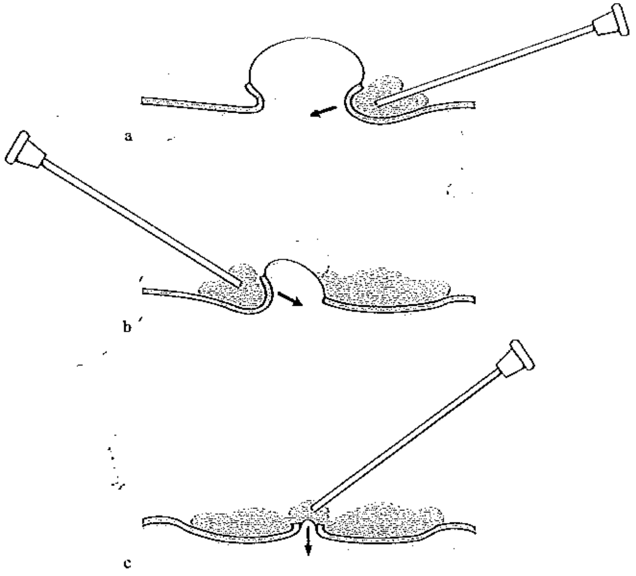


Fig. 8.108. Reduction of an intact vitreous prolapse with viscoelastic material

a Starting from the periphery of the capsule and working toward the center, a "viscoelastic spatula" is injected toward the everted capsule margin to push it back toward the prolapse and hold it in place.

b This procedure is continued all around the lesion until the capsule margins are so positioned that pressure from above will no longer evert them. Contained in this way by viscoelastic material, the prolapse can only move downward when compressed from above.

c Finally viscoelastic material is injected onto the prolapse from above, effecting the reduction



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[64] *Note*: As the pressure rises the air bubble is compressed. Successful pressure increase, then, is recognizable by a discrepancy between the amount of injected air and the resulting increase in bubble size.

Fig. 8.109. **Space-tactical situations after evacuation of the capsular bag**

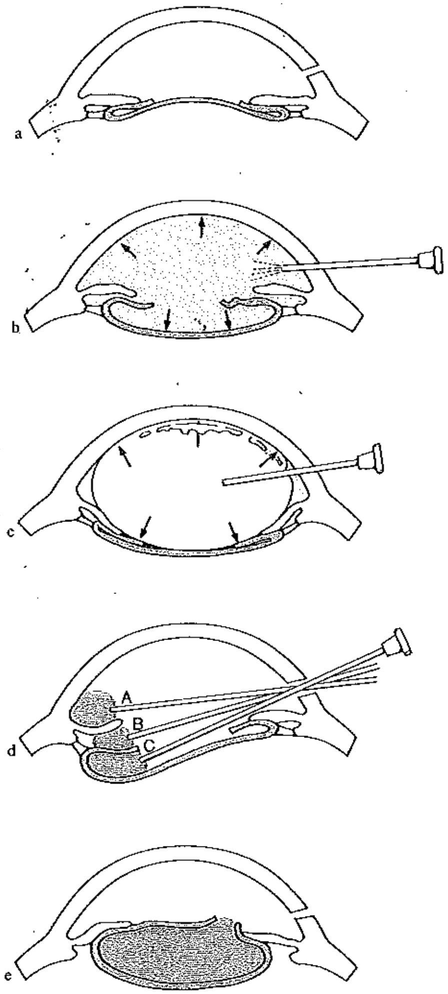
a Obliteration of the retroiridal subcompartments. Any forward motion of the diaphragm following evacuation of the capsular bag will restrict the interspaces between the iris, anterior capsule, and posterior capsule.

b Reformation of the anterior chamber with watery fluid. As the anterior chamber is repressurized, the posterior capsule is restored to its anatomic position. The position assumed by the iris and anterior capsule remnants depends on their tissue tension. The iris moves onto the plane of the iris root. The tension of the anterior capsule remnants depends on the size and shape of the capsulectomy.[65]

c Obliteration of the subcompartments by air injection. The air pressure chamber opens the chamber angle but depresses the iris against the capsule layers, narrowing the spaces between them.

d Selective reexpansion of the subcompartments by injection of viscoelastic material into the chamber angle (*A*), the iridocapsular interspace (*B*), and the intercapsular space (*C*).

e Separation of the anterior and posterior capsule layers in the presence of a small capsulotomy. Total visco-occupation of the collapsed capsular bag restores its shape and increases its tension



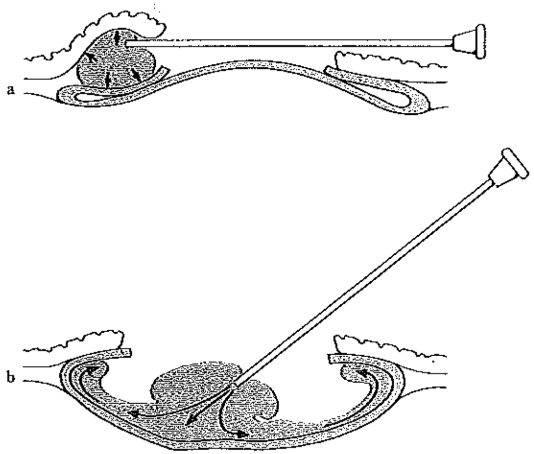


Fig. 8.110. **Selective placement of viscoelastic material in the iridocapsular or intercapsular interspace**

a Expansion of the *iridocapsular* interspace. The cannula tip elevates the iris away from the anterior capsule, and the viscoelastic material is injected toward the undersurface of the iris. This presses the anterior capsule against the posterior capsule and prevents viscoelastic material from entering the space between the capsule layers.

b Expansion of the *intercapsular* space. The posterior capsule is pressed back away from the anterior capsule by first injecting the viscoelastic material toward the center of the posterior capsule (center of the pupil). From there the material spreads peripherally along the surface of the posterior capsule, thereby expanding the space between the two capsule layers

Measures on the Lens Capsule Relating to the Insertion of Intraocular Lenses

The iridocapsular and intercapsular spaces may become obliterated following evacuation of the capsular bag. The anterior capsule tends to fall back onto the posterior capsule, and both capsule layers may appose to the undersurface of the iris (Fig. 8.109a). This makes it difficult to position a retropupillary IOL accurately.

Selection of Pre- and Intercapsular Insertion Sites

Selective reopening of the desired intraocular compartment for positioning the supporting loops of an IOL is a problem of spatial tactics.

If the space is reexpanded with **watery fluid**, it is necessary first to restore the anterior chamber as a pressure chamber. This requires a wound closure that can retain sufficient watertightness during the insertion maneuver.[66] A satisfactory space can usually be developed between the capsule layers and the iris. Success in separating the anterior and posterior capsule layers themselves depends on the tension of the anterior capsule. This is influenced by the shape of the anterior capsulotomy (Fig. 8.109b) and cannot be increased secondarily by the injection of watery fluid.

Basically, **air injection** merely enlarges the anterior chamber. It removes the corneal endothelium from the field of manipulations and widens the chamber angle. However, the iris and capsule layers are pressed backward as a unit, and the interspaces among them are compressed (Fig. 8.109c).

The different compartments can be selectively shaped with **viscoelastic materials**. The iridocapsular and intercapsular spaces can be expanded segmentally or over their whole circumference (Fig. 8.109d, e).

The *selective placement* of viscoelastic material into subcompartments is easy if the remnants of the anterior capsule are plainly discernible. However, if the capsule remnants are not accessible, the viscoelastic material may be injected toward the adjacent membranes, i.e., toward the iris to press it forward or toward the posterior lens capsule to press it backward (Fig. 8.110). If the posterior capsule is breached, the rupture site must first be tam-

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[65] A plain circular capsulectomy may leave the capsule remnants tense, whereas an excision with angled or jagged edges relieves tension and leaves tags of tissue that float in a watery medium.

[66] Requirements in this regard depend on the level of the vitreous pressure, for an equal level must be established in the anterior chamber to restore a normal chamber depth and normal anatomic relations within the eye.

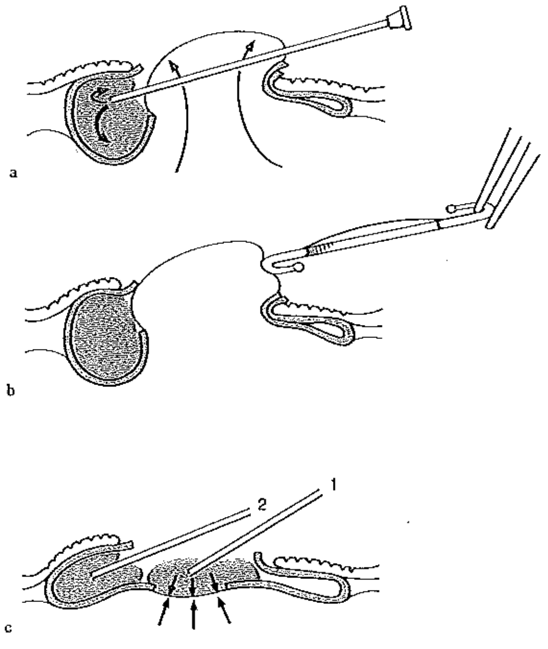

Fig. 8.111. Expanding the peripheral compartments following rupture of the posterior capsule

a Expansion of the retroiridal space by injected viscoelastic material causes compensatory vitreous prolapse through the rupture site.

b This prolapse, often invisible within the viscoelastic medium, prevents the placement of IOL haptics behind the iris.

c The first step, then, is to tamponade the rent in the posterior capsule (see Fig. 1.23) before proceeding to expand the retroiridal space

ponaded before the subcompartment is expanded peripherally (Fig. 8.111).

The use of viscoelastic materials has the additional benefit of increasing the tension of the capsule and smoothing it out so that implants can glide over the capsule surface without becoming snagged in folds. Further, "visco-occupation" of the anterior chamber can immobilize the implant in any position along its insertion path without the need for instrument fixation. Thus, malposition of an implant during insertion can be corrected by releasing the IOL, reorienting it, regrasping it in a better position, and guiding it optimally to the implantation site.

The increased resistance of the viscoelastic material, however, can cause the implant to deviate from the intended path during insertion either at the surface or within the viscoelastic bolus itself. **Deflection** at the *interface between a liquid and viscoelastic medium* (Fig. 8.112) is best avoided by eliminating such interfaces altogether, i.e., by placing the viscoelastic material along the entire insertion route from the corneoscleral incision to the implantation site. If the implant must traverse an interface, the degree of the deflection is minimized if it is passed through at an angle approaching 90°.

Deflection can even occur *within the viscoelastic medium itself* when the moving implant presents an angled surface to the medium (Fig. 8.113). The asymmetrical resistances that produce this deflection are unavoidable during the insertion of an angulated implant; however, the effect of these resistances can be reduced by inserting the implant very slowly.

In practice, deflection is mainly a problem when an implant with soft, elastic supporting haptics is used. If the implant is handled by those haptics during insertion, their elasticity will provide the force for guiding the optic portion into the desired position. This elasticity is opposed by the elastic resistance of the viscoelastic material beneath the optic portion, which tends to repel the implant and push it back.

Once the implant has been maneuvered to its definite position, it must be held in that position for a moment so that the surrounding viscoelastic material can yield and stabilize. If the haptics are released too soon, the molecular chains will not have time to rearrange below the implant, and they will repel it from the desired position.

If the resistance of the viscoelastic material is too high in relation to the elasticity of the haptics (as in implants with a large optic portion), it becomes impossible to insert the implant by manipulation of the haptics. The larger the optic portion, the more one has to rely on techniques in which the implantation instrument grips the optic portion of the IOL directly (Fig. 8.114).

8.112

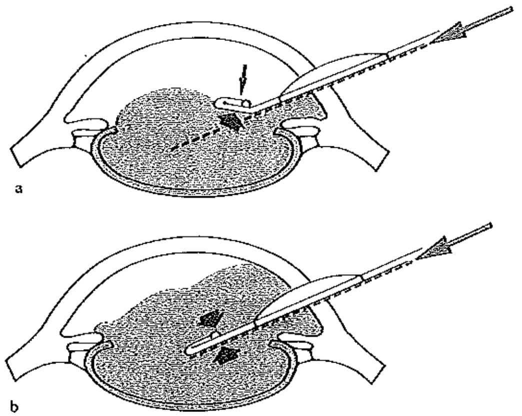

Fig. 8.112. Deflection of soft haptics at the interface between liquid and viscoelastic media

a If viscoelastic material has been injected only into the deep portions of the anterior chamber, the resistance at the interface is higher on the side of the viscoelastic material (*wide arrow*) than on the side of the watery fluid (*thin arrow*). Deformable haptics are deflected and cannot be inserted behind the iris.

b If the viscoelastic material forms a continuous medium from the corneal incision to the destination, the haptics encounter equal resistances above and below, and deflection does not occur

8.113

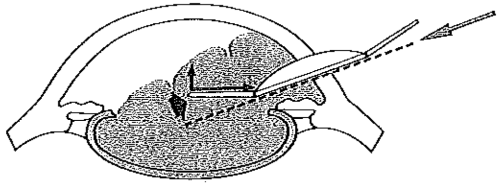

Fig. 8.113. Deflection tendencies within the viscoelastic medium. If the haptics are positioned at an angle to the optic portion of the implant, they will encounter asymmetric resistances when the implant is moved on the plane of the optic portion. Resistance to the motion of the haptic (*medium arrow*) has a component that exerts an upward force on the haptic (*wide arrow*)

8.114

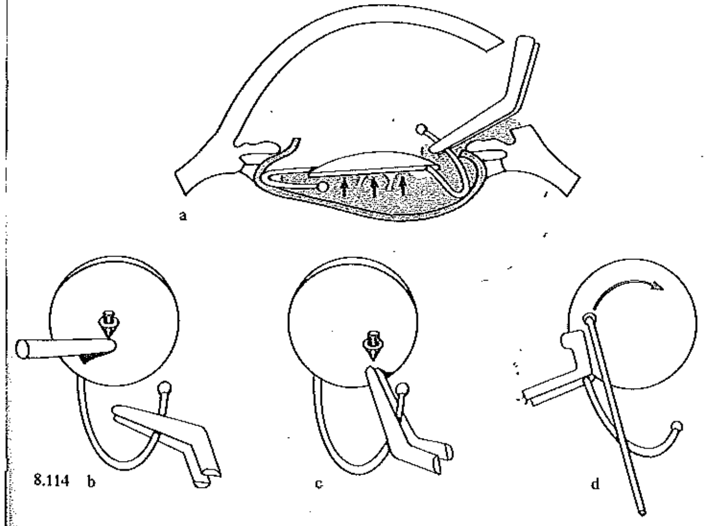

Fig. 8.114. Overcoming viscoelastic resistance to the optic portion of an IOL

a Viscoelastic material in the capsular bag offers high resistance against placement of the large optic portion of an implant.

b This resistance can be overcome by pressing the optic portion downward with a spatula.

c The implantation forceps itself, if properly shaped, can be used to exert counterpressure on the optic portion of the IOL. Note that while in **a** the haptic is gripped with the tips of the forceps, here it is gripped farther back on the forceps, whose tips can then project over the optic portion and push it down.

d Here the optic portion is seated with a laterally applied insertion spatula whose front surface has a guide slot. (The back surface of the spatula is hook-shaped for retraction of the iris and lens capsule)

Artificial Capsule for Aiding IOL Insertion

The lens capsule provides a useful guide surface for the placement of retropupillary IOLs. Through its resistance, it can direct the haptics of the implant to their fixation sites in the ciliary sulcus or intercapsular sinus. Without this guide surface, it is difficult to keep the haptics on the intended path.

If the lens capsule is absent following an intracapsular delivery or an extensive tear of the posterior capsule, an *artificial guide surface* can be formed by utilizing the membrane-like properties of interfaces. This is done by injecting an air bubble behind the pupil and holding it in place by filling the prepupillary space with viscoelastic material (Fig. 8.115). The haptics of the implant are applied to the surface of the bubble at small angles so that they glide along its surface and do not penetrate it. In that way they can be safely guided through the pupil and along the posterior face of the iris into the ciliary sulcus.

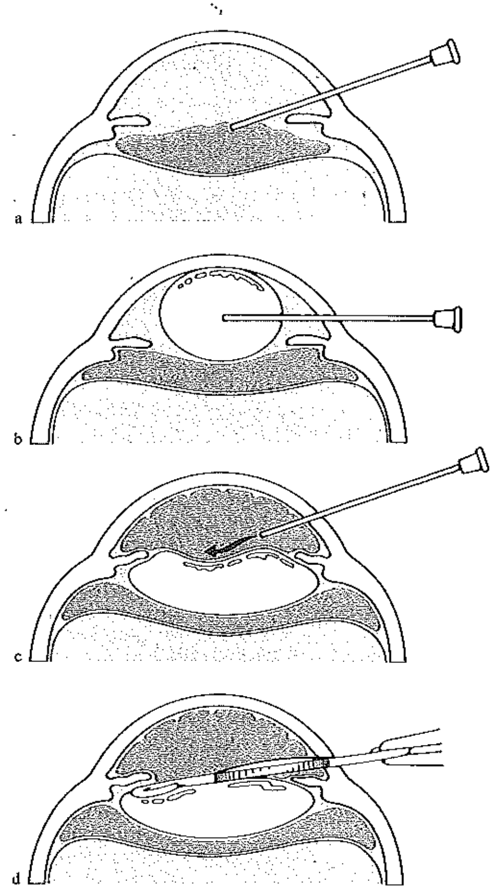

Fig. 8.115. **"Air sandwich" as an artificial lens capsule**

a A protective layer of viscoelastic material is placed over the vitreous surface. This layer should just cover the anterior hyaloid as a protection. If too much material is injected, there will be insufficient volume for the subsequent injections during steps b and c.

b An air bubble is injected above that layer.

c Another layer of viscoelastic material is injected above the air bubble, pressing the bubble down behind the pupil.

d The *haptics* of the intraocular lens glide along the bubble surface into the ciliary sulcus. The buoyancy of the bubble keeps the *optic portion* of the implant elevated and holds the IOL against the undersurface of the iris

9 Anterior Vitrectomy

9.1 General Problems of Surgical Technique

Anterior vitrectomy in the present context refers to the excision and removal of dislocated vitreous tissue, i.e., of structurally normal vitreous that has accidentally prolapsed from its natural position into the anterior chamber or even out of the eye.[1] The major clinical problem in such vitreous dislocations are adhesions on anterior segment tissue surfaces (wound, posterior corneal surface, iris), which may transmit traction to the retina in the postoperative period.

The **goal** of *anterior vitrectomy*, then, is to eliminate such adhesions and ensure that no new adhesions will form. This means that existing vitreous adhesions are cleared, vitreous that has prolapsed into the anterior segment is removed, and sufficient volume is removed from the vitreous chamber itself to ensure that no additional fibers will herniate back into the anterior segment.

The **prevention** of adhesions is a matter of *protecting tissue surfaces* from vitreous contact, and this is a problem of surface tactics. Viscous and viscoelastic protective coatings are an effective prophylaxis whenever the possibility of undesired vitreous contact is anticipated.

From the standpoint of *surgical technique*, vitreous is a difficult tissue to manipulate. It is not compact enough to be held with a grasping instrument (e.g., forceps), it is not sectile enough to be cut with precision, and it tends to adhere to tissue or instrument surfaces with which it comes in contact.

Vitreous can be **grasped** with suction instruments such as sponges or aspiration cutters. When *sponge swabs* are used, the sucking force of capillary attraction is reinforced by the tendency of the vitreous to adhere to the rough surface of the sponge. However, sponges are difficult to control as grasping instruments – the amount of vitreous grasped is difficult to define, and material that has been grasped cannot be released. Moreover, the volume of the sponge expands through fluid uptake, and its rough surface may scrape against delicate intraocular tissues such as the corneal endothelium. Consequently, sponge swabs are best suited for use on the ocular surface. For **cutting** the vitreous, instruments are needed which limit shifting of the tissue in front of the cutting edge and thus improve its sectility. *Scissors* must have long blades to compensate for forward shifting of the vitreous by the cutting point.[2] For optimum cutting effect, scissors should be applied at sites where the shifting tendencies of the tissue are constrained, e.g., close to a grasping sponge or at the margins of an incarcerating incision.

In *suction cutting instruments*, the cutting action is most efficient when the blade is either applied directly at the site where the tissue is held fast by suction (see Fig. 2.88) or when the blade moves so rapidly that the inertia of the tissue keeps it from shifting (see Fig. 2.89). Owing to their small dimensions, suction cutters are excellent for use in the interior of the eye. They are less suitable for use on the ocular surface, for there the vitreous layer is too thin for establishing and maintaining occlusion. Air is aspirated, and once this occurs, control of the suction is lost.[3]

All manipulations on the vitreous are associated with *traction*. The potential for stress transfer from vitreous to retina thus depends on **anatomic factors**, i.e., the distensibility and resistance of the vitreous fibers and the condition of the vitreoretinal attachments.

Relatively compact vitreous with a *homogeneous* structure (Fig. 9.1 a) can transmit traction to the retina regardless of the site where the traction is applied (Fig. 9.3 a). If the vitreous is *differentiated* into a relatively fluid center surrounded by a more compact cortex (Fig. 9.1 b), traction on the central vitreous will

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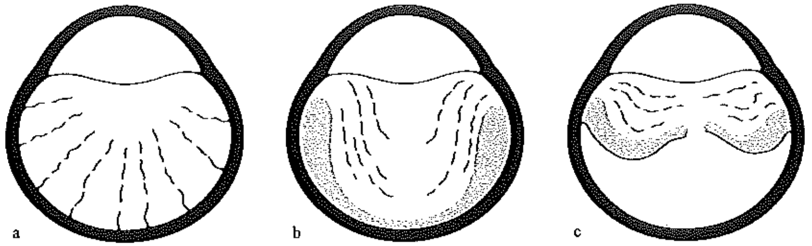
[1] By contrast, posterior vitrectomy is concerned with pathologic vitreous structures that have remained in their natural compartment.

[2] Conversely, scissors with short blades are appropriate for posterior segment vitrectomy, because there the targets are fibrotic strands that are more sectile than normal vitreous.

[3] Air bubbles, unlike fluid, are distensible and compressible. They behave as elastic cushions that can store energy and release it abruptly. Phases of inadequate suction (below the instrument setting) alternate with phases of excessive suction (above the instrument setting), posing a danger to neighboring tissues (analogous to elastic tubing, see Fig. 1.9). Once air bubbles have gained entry, the instrument and tubing system must be purged of air before reuse.



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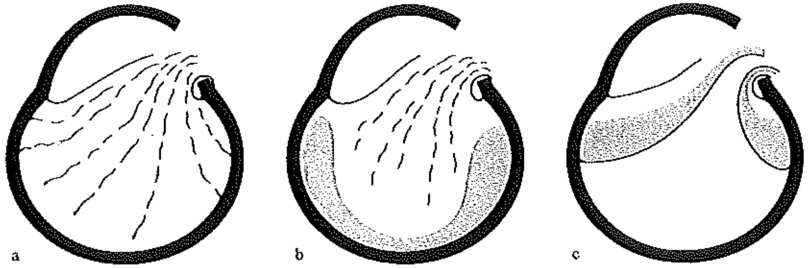

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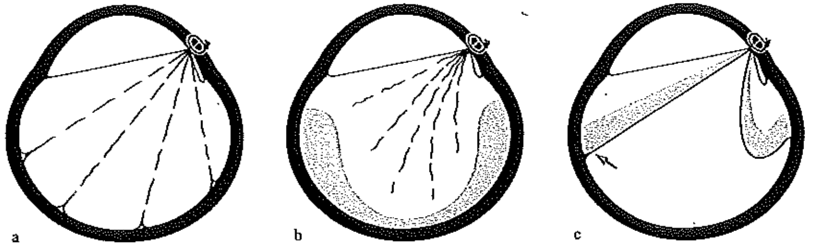

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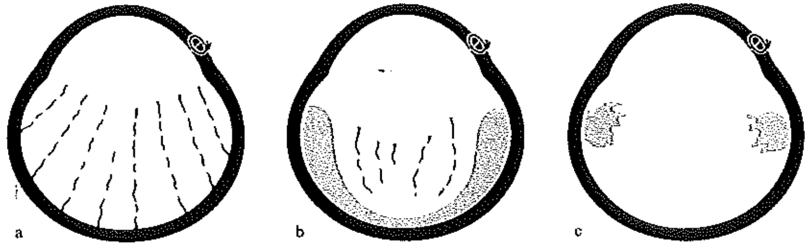

9.4

Fig. 9.1. **Structure of the vitreous**[4]

a In youth the vitreous has a practically homogeneous structure with no demarcation between the central vitreous and cortex. All the vitreous tissue is semisolid and therefore distensible while still being structurally cohesive.

b With aging, the vitreous undergoes a structural change characterized by the demarcation of a semifluid central substance and a relatively compact cortex. This cortex forms a 1–3 mm thick layer lining the entire retina (*dark gray*). The central substance extends to the ciliary epithelium anterior to the ora serrata and is bounded in front by the anterior hyaloid.

c In posterior vitreous detachment, the retinal surface loses contact with the vitreous as far as the posterior boundary of the vitreous base. The compact vitreous cortex remains adherent only to the most peripheral parts of the retina

Fig. 9.2. **Structure of a vitreous prolapse**

a In young patients the prolapse contains fibers that can transmit traction directly to the retina.

b In adult patients the prolapse consists of the semifluid central substance while the peripheral cortical layers (and their connections with the retina) may remain unaffected.

c In posterior vitreous detachment the prolapse also includes cortex that has strong connections with the peripheral retina

Fig. 9.3. **Status following resection of the external vitreous prolapse.** Patterns of vitreous incarceration where management of the prolapse has been confined to excision of the expelled tissue and subsequent wound closure.

a In young patients the incarcerated vitreous contains relatively tense fibers that have direct attachments with the entire retinal surface.

b Incarcerated adult vitreous contains lax fibers that have attachments with the undisplaced vitreous cortex. This cortex may act as a buffer against the transmission of tension from the wound to the retina.

c Following posterior vitreous detachment, the cortex and the posterior hyaloid are incarcerated in the wound. Any subsequent contraction of the cortex will mainly affect the vitreous base on the opposite side of the wound (*arrow*)

Fig. 9.4. **Criteria for an adequate anterior vitrectomy.** Resection of a volume sufficient to prevent recurrence of the prolapse.

a If the vitreous is semisolid, its relatively compact structure makes postoperative relapse unlikely, so resection of only a small part of the retrolenticular vitreous may suffice.

b With a liquid central vitreous, there is a greater danger of relapse, so a greater volume of the central substance has to be removed. However, the cortex and its connections to the retina must not be disturbed.

c Following posterior vitreous detachment, anterior vitrectomy becomes a subtotal vitrectomy that leaves only a narrow rim of cortex along the vitreous base

have little effect since stress transfer through a fluid medium is poor and is additionally buffered by the cortex. However, direct traction on the cortex is transmitted extensively to the retina (Fig. 9.3b). In *vitreous detachment* (Fig. 9.1c), the cortex remains attached to the retina only at the vitreous base.[5] Consequently traction is transferred only to the retinal periphery while having no effect on the posterior segments of the retina (Fig. 9.3c).

Thus, the nature of the vitreous structure has a major bearing on the management of vitreous prolapse. From the standpoint of surgical tactics, there is a basic distinction between:

- the prolapse of nondetached vitreous (structurally homogeneous or differentiated into central substance and cortex, Fig. 9.2a and b) and
- the prolapse of detached vitreous (Fig. 9.2c).

The prolapse of **nondetached** vitreous involves the herniation of central substance. Depending on the compactness of the tissue, traction on the prolapsed vitreous may either have no effect, or it may jeopardize all portions of the retina (Fig. 9.3a, b). With the prolapse of **detached** vitreous that includes the herniation of vitreous cortex and posterior hyaloid, traction will endanger the peripheral retina but will not threaten the posterior retina (Fig. 9.3c).

Regarding the **quantity** of vitreous that must be excised to prevent a recurrence of vitreous prolapse into the anterior segment, it is sufficient to remove the anterior central substance in the *nondetached* vitreous (Fig. 9.4a, b). In the *detached* vitreous, however, the excision should include the detached vitreous cortex while leaving only the portion attached at the vitreous base (Fig. 9.4c).

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[4] For details see G. Eisner, Clinical anatomy of the vitreous, T.D. Duane and E.A. Jaeger, Biomedical Foundations of Ophthalmology, Harper & Row, 1982, Chap. 16.

[5] In juveniles the posterior limit of the vitreous base is at the ora serrata, so the cortex can become detached as far as the ora serrata. With aging, the vitreous base migrates toward the equator, so vitreous detachment terminates somewhere between the ora serrata and equator.

9.2 Strategic Decision-Making Criteria in Vitreous Prolapse

Vitreous prolapse results from a rise of pressure in the vitreous chamber. The *sources* of this pressure rise may be external factors, which act on the globe from the outside, or internal factors that arise within the eye itself. Each of these two causes demands totally different responses from the surgeon. Thus, when vitreous prolapse is recognized, it is important to establish at once whether external or internal factors are causative.

The **external factors** are deforming forces which indent the scleral coat of the vitreous chamber (see Fig. 1.42c) or forces which press the diaphragm downward (see Figs. 1.53, 8.2a). Usually the external cause can be eliminated quickly, whereupon the vitreous pressure will return spontaneously to the previous level without any further intervention by the surgeon. Once the vitreous pressure has returned to a low level, there is no danger of further vitreous loss.

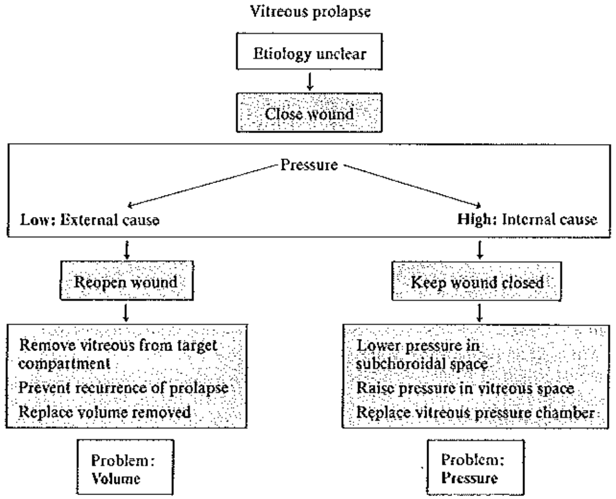
The situation is quite different when the prolapse is caused by **internal factors**. Here the mass effect in the vitreous chamber is caused by a pressure rise in the retrochoroidal space secondary to extravasation from the choroidal vessels (expulsive hemorrhage).[6] This extravasation will persist until the intraocular pressure equals that of the leaking vessel. Treatment strategy, then, aims at raising the intraocular pressure to a sufficient level promptly before too much of the intraocular volume is expelled.

The flowchart in Table 9.1 shows the *decision-making criteria* for the intraoperative management of vitreous prolapse. If there is the least suspicion of expulsive hemorrhage, the incision should be closed at once and secured against the further expulsion of vitreous. Only then may the situation be assessed in detail. First, any external deforming factors are eliminated. Subsequent measures are determined by the intraocular pressure:

If the pressure *falls* after elimination of the external factors, the prolapse obviously was caused by them. The incision may be reopened, and further measures consist in evacuating the herniated vitreous. The essential problem is one of *volume*.

If the intraocular pressure is *high*, choroidal hemorrhage is presumed, and the incision should remain closed. Further measures are directed toward lowering the pressure in the retrochoroidal space while raising the pressure in the vitreous chamber. The essential problem is one of *pressure*.

Table 9.1



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[6] The rate of expansion of the retrochoroidal space depends on the pressure in the bleeding vessel. Thus, the rate of vitreous prolapse is high with bleeding from the larger ciliary arteries but is much slower with venous bleeding.

9.3 Anterior Vitrectomy for Vitreous Prolapse Caused by External Factors

The anterior vitrectomy consists of four phases (Fig. 9.5):

- removal of extraocular vitreous;
- removal of vitreous from the wound surfaces;
- removal of vitreous from the anterior chamber;
- clearing of an additional volume ("safety zone") adequate to prevent postoperative recurrence.

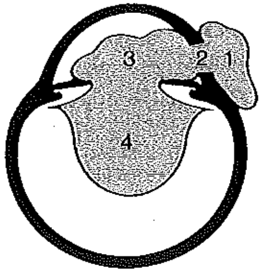


Fig. 9.5. **Parts of a vitreous prolapse removed by anterior vitrectomy**
1 Extraocular prolapse
2 Prolapse within the incision
3 Prepupillary prolapse
4 Retropupillary safety zone (see Fig. 9.4)

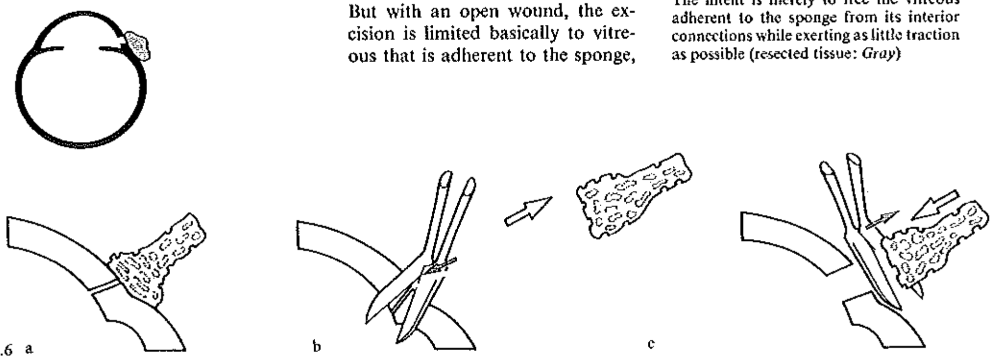
Extraocular vitreous is removed as close to the ocular surface as possible so that all the prolapsed tissue is excised. The technique of this phase varies according to whether the incision is closed or open.

In a tightly **closed incision** the prolapsed vitreous is incarcerated between the wound lips, and traction on its exterior portion will not be transmitted into the eye interior. Therefore, maximum traction on the prolapse is safe and can be used for exploiting the retractile tendency (see Fig. 2.64) to place the excision as close to the ocular surface as possible. The scissor cut is made directly over the wound, where sectility is greatest owing to the incarcerated tissue; i.e., the cut is made far from the grasping sponge (Fig. 9.6b).

With an **open incision**, any traction on the prolapse may jeopardize the intraocular tissues, so all measures should involve a minimum of traction. Sponge swabs grasping the prolapse should be lifted just enough to allow scissors to be applied; thereafter they are held stationary. The scissor cut is made adjacent to the sponge (Fig. 9.6c).

In each of the two situations above, different means are used to *control the extent of the vitrectomy*. With a closed incision, the quantity of excised vitreous can be influenced by *traction* to the prolapse. But with an open wound, the excision is limited basically to vitreous that is adherent to the sponge, so the extent of the excision is increased by *repeating* the grasping and cutting maneuver.

Vitreous removal **from the wound surfaces** is effected by applying outward or inward traction. For an *ab externo* removal, the upper part of the prolapse is freed by elevating the upper flap of the incision. Then the prolapse itself is grasped with sponge swabs and wiped from its attachments with the lower wound surface. At the wound angles, however, the upper flap cannot be raised enough to provide sufficient space for maneuvering the sponge. Thus, removal of vitreous incarcerated at the angles may require a lateral extension of the incisions



9.6

Fig. 9.6. **Removal of prolapsed vitreous from the outer surface of the eye**

a The vitreous is grasped with a sponge swab right at the incision so that the prolapse can be resected as close to the ocular surface as possible.

b If the incision has been closed, the vitreous is lifted with the sponge and put on maximal stretch to exploit its retractile tendency (*large arrow*). The scissors are pressed *close to the ocular surface* when the resection is performed (*small arrow*).

c If the incision has remained open, the vitreous is lifted only slightly, and the scissors are applied *close to the sponge*. The intent is merely to free the vitreous adherent to the sponge from its interior connections while exerting as little traction as possible (resected tissue: *Gray*)

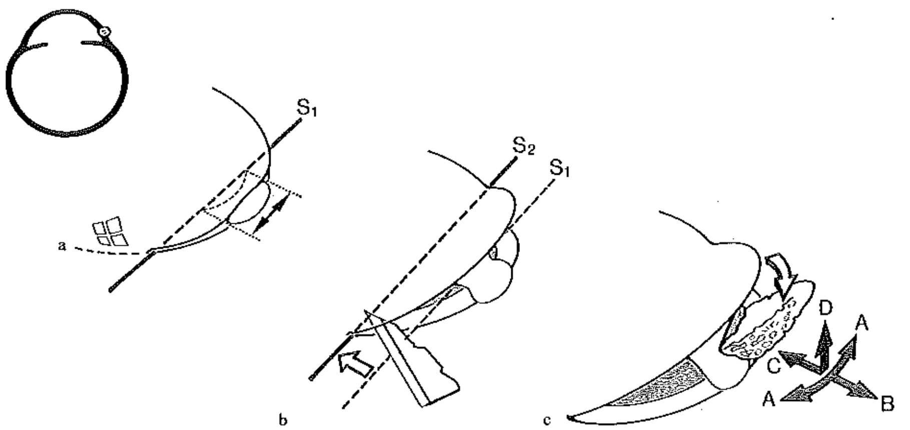


Fig. 9.7. **Freeing vitreous incarcerated between the wound lips. Extension of the wound for gaining access to the lateral edges of the prolapse.**

a Vitreous is incarcerated to the outermost corners of a wound with a given length *L*.
S_1: Hinge axis.

b The extension moves the hinge axis from S_1 to S_2. The new hinge position allows the upper wound surface to be raised from the lower wound surface beyond the lateral edges of the prolapse; now the wound surfaces lateral to the prolapse are free of vitreous. Further with a more posterior position of the hinge, the corneal endothelium on the fold is moved away from the range of action of the sponge swab.

c Clearing the vitreous adhesions begins by wiping the sponge from the vitreous-free wound surfaces toward the center of the prolapse. The optimum direction for this action is parallel to the wound line for separating the adhesion (*A*) and horizontally away from the wound margins for applying traction (*B*). Motion toward the wound (*C*) or upward (toward the upper wound surface, *D*) jeopardizes the endothelium

(Fig. 9.7a). The new hinge axis will then allow the flap to be raised above the lateral borders of the prolapse (Fig. 9.7b, c), reducing friction and facilitating the lysis of adhesions, and all wiping maneuvers with the sponge can proceed from clean wound surfaces toward the prolapse. Vitreous removal by *inward* traction relies on an indirect transfer of forces. But this transfer is hampered by the extreme compliance of the vitreous, so forces are most effective when applied at sites where the compliance of the vitreous is reduced by other tissue (i.e., where the vitreous surface is covered by *iris*, Fig. 9.8) or by an instrument (e.g., an *air bubble*, Figs. 9.9, 9.10).

When vitreous is removed from **the anterior chamber**, unnecessary traction can be avoided only when the grasping and cutting instruments are introduced into the chamber. Vitrectomy with sponge and scissors basically follows the technique shown in Fig. 9.6c, except that there are greater space limitations, and expansion of the sponge threatens surrounding tissues (Fig. 9.11a). Providing sufficient space for safe maneuvering may require wound extension, which not only will give better access for insertion of the instruments but will also protect the endothelium at the hinge fold by moving the hinge axis out of the danger zone for manipulations (Fig. 9.7b). All vectors of instrument motion are directed away from the posterior corneal surface.

The use of a *suction cutter* (Fig. 9.11) largely eliminates the problem of restricted space. Traction effects are minimized by using a high cutting frequency.[7]

For the **removal of retroiridal vitreous**, the instruments must be inserted behind the iris. The sponge-and-scissors technique requires that the incision be widely opened so that the hinge axis is beyond the pupil margin (i.e., far more than 180°).[8]

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[7] The relationships between cutting frequency and suction are discussed on p. 84. A traction-free vitrectomy is initiated at a high cutting frequency, and the frequency is gradually reduced until a suction effect is apparent.

[8] This method may be used, therefore, when vitrectomy is performed in conjunction with a perforating keratoplasty.

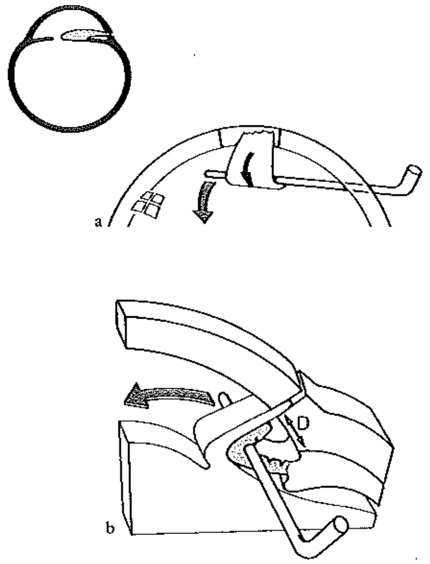

Fig. 9.8. **Freeing incarcerated vitreous with a spatula toward the inside. With the wound closed, a spatula is inserted beneath the prolapse. For access there must be an adequate distance (*D*) from the interior wound opening to the iris root.**

a Principle of the method: A slender spatula is passed beneath the prolapse and swept toward the center of the anterior chamber.

b A spatula thin enough to be introduced into the narrow interspace between the inner wound lip and chamber angle presents such a small surface area that the vitreous structures may yield to the spatula more readily than the vitreous adherent to the wound surfaces. Thus, the sweeping maneuver is more effective when the deep surface of the prolapse is covered by everted iris, and the spatula can engage against its compact surface

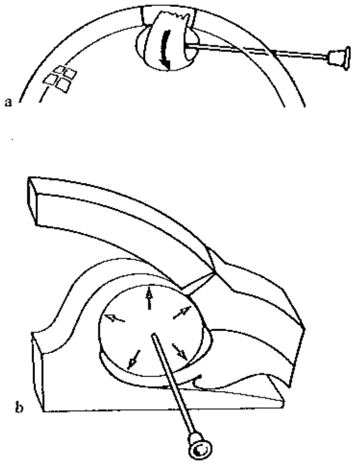

Fig. 9.9. **Freeing the incarcerated vitreous with an air bubble**

a If iris does not cover the vitreous surface, an air bubble can be used as a "bullous" spatula to apply force to the prolapse more diffusely.

b The cannula is passed below the prolapse, and air is injected

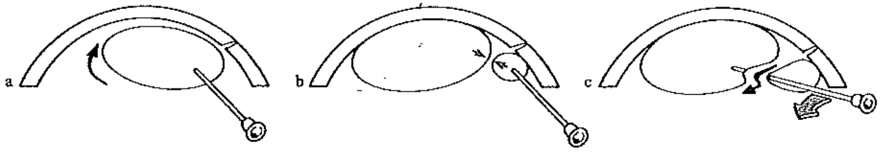

Fig. 9.10. **Use of double air bubble in very compliant vitreous**

a The vitreous may be so compliant that an air bubble placed beneath the incarceration (i.e. at the chamber angle) merely stretches it without extracting it from the incision.

b Vitreous compliance is exhausted by injecting a second large bubble above the incarceration (i.e. between the corneal dome and the surface of the prolapse).

c Thus immobilized, the incarcerated vitreous can be pulled from the wound with a sweeping motion of the cannula. The two bubbles will coalesce when the incarceration is relieved

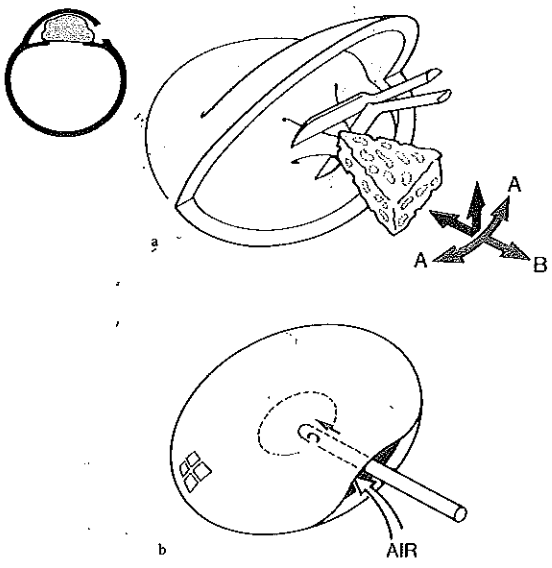

Fig. 9.11. **Evacuation of vitreous from the anterior chamber.** Removal of prepupillary vitreous (*inset*).

a A large incision is required for insertion of the sponge swab and scissors; the space must also be sufficient for the anticipated expansion of the sponge. Motions of the sponge parallel to the iris plane, outward (*A*), and laterally (*B*) pose the least danger to the endothelium. Motion directions inward or upward (*black arrows*) are the most hazardous.

b Use of a suction cutter. Motion of the instrument is toward the pupil so that no vitreous is dragged against tissue surfaces to which it could adhere. The incision is held open so that air can enter and facilitate evaluation of the extent of the anterior vitrectomy. However, the aspiration port of the cannula should not come in contact with air and should remain surrounded by fluid; otherwise air would get into the tubing system

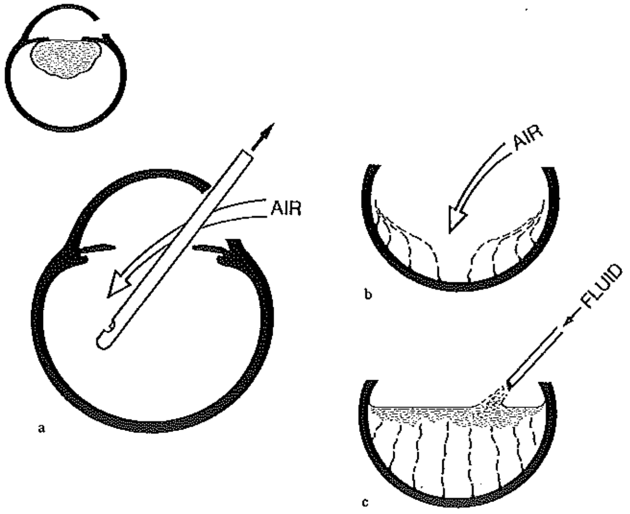

Fig. 9.12. **Removal of vitreous from the vitreous chamber.** Resection of retropupillary vitreous to prevent postoperative relapse into the anterior chamber (see Fig. 9.4).

a Insertion of the suction cutter behind the pupil. To avoid the aspiration of peripheral vitreous, the tip should not stray from the central axis of the globe. Air is allowed to enter through the open incision to replace the aspirated volume.

b Air as an indicator: Due to surface tension, air displaces the vitreous fibers backward, and the vitreous face becomes spherically concave.

c If the air is subsequently replaced by fluid, the vitreous fibers will move forward again and reassume their anatomic position. This "fluid indicator" maneuver thus demonstrates that the excision has cleared less vitreous than the "air indicator" suggested

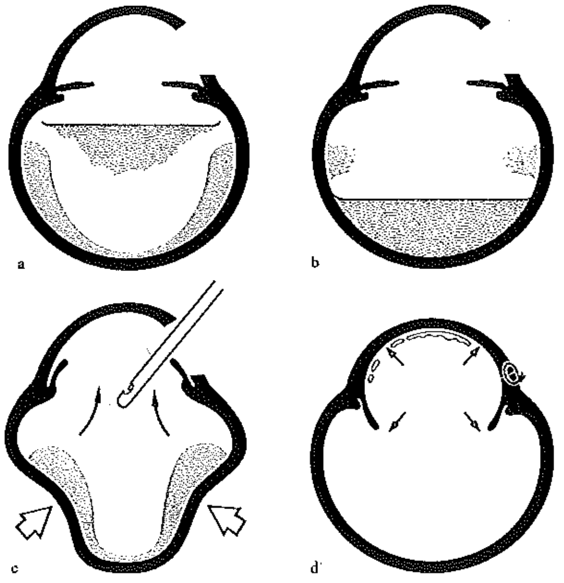

Fig. 9.13. **Criteria for evaluating the extent of the vitrectomy**

a Nondetached vitreous. The iris (and, if present, the perforated lens capsule) are exposed to the open air. If the underlying meniscus is flat at its center, it signifies a pool of watery fluid over the completed vitrectomy.

b Detached vitreous. A pool of watery fluid remains behind the remnants of the vitreous base. The fluid surface is level.[12]

c Absence of compensatory air inflow. The lack of air inflow during vitrectomy is a warning sign. It signifies that the vitreous is coming forward, and preretinal vitreous cortex may move into range of the suction tip. This is caused by deformation of the vitreous compartment by a rise of choroidal or orbital pressure.

d Air injection with a closed wound. While air entering an open chamber serves only as an indicator for the aspirated fluid volume, air injected in the presence of an airtight wound has an entirely different function: It forms an artificial pressure chamber able to exert counterpressure against external forces. However, its deforming effect on surrounding structures makes it a poor indicator of vitreous topography

Suction cutters, on the other hand, can be introduced deeply through a small incision (Fig. 9.12). Retinal traction during the vitrectomy is avoided by keeping the tip opening close to the axis of the globe. This reduces the risk of aspirating vitreous cortex (i.e., the whole cortex in a nondetached vitreous, or the cortex at the vitreous base in a detached vitreous).[9]

Vitreous adhering to wound surfaces cannot be cleared with suction cutters, so when the operator has completed the deep vitrectomy he should reexplore the wound with sponge swabs to confirm that the surfaces and corners of the incision are clear.

Visual monitoring of the extent of the vitrectomy is difficult in a *watery* or *viscoelastic* medium due to lack of contrast with the transparent vitreous structures.[10] The extent of the excision can be assessed by indirect signs such as displacement or deformation of adjacent tissues by relatively solid vitreous structures or movements imparted by instrument manipulations -- but the absence of these signs does not prove that the vitrectomy is complete.

A more reliable method of defining the evacuated space is by *space occupation with air*. This is done in anterior vitrectomy by holding the incision open and allowing air to enter and replace the aspirated vitreous. The depth of the excision is then evaluated by noting the location and shape of the residual vitreous surface.[11] However, air may be deceptive as an indicator because the surface tension of the air bubble displaces the vitreous fibers (Fig. 9.12b), which later reassume their original position after the air has been absorbed and replaced by aqueous. Consequently the extent of the vitrectomy may prove to be much smaller postoperatively than it appeared at operation. To confirm that a vitrectomy has been carried to the desired depth, *fluid* may be injected when the apparent target depth has been reached (Fig. 9.12c). The residual vitreous

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[9] This operation contrasts with posterior vitrectomy, where surgery is performed close to the retinal surface and the tip opening may be placed close to the retina to peel away vitreous and membranes.

[10] Recall that anterior vitrectomy, unlike posterior vitrectomy, is performed on normal vitreous that is completely transparent.

[11] In anterior vitrectomy, therefore, intially no fluid is infused for volume replacement.

[12] When the resection of detached vitreous reaches the retrovitreous space during the vitrectomy, the rate of air inflow increases abruptly due to the faster evacuation rate of the watery retrovitreous fluid (lower resistance to aspiration) compared with the vitreous.

will level off in the injected fluid medium. Additional vitrectomy may then be performed if need be, and this maneuver can be repeated several times. When there is no more vitreous below the air bubble, only watery fluid, the interfacial meniscus will flatten out and the fluid level will appear flat-surfaced at the center (Fig. 9.13).

An *absence of air inflow* through the open incision during anterior vitrectomy is a warning sign that there is an elevated pressure in the vitreous space as a result of choroidal or scleral compression (Fig. 9.13c). Vitreous cortex then may bulge toward the center and become caught by the suction cutter, posing an imminent threat to the retina. The remedy is to produce a counterpressure against the deforming forces by restoring the pressure chamber of the vitreous. This is done by closing the wound and injecting air to create an artificial pressure chamber (Fig. 9.13d).

9.4 Management of Vitreous Prolapse Caused by Internal Hemorrhage

With bleeding from choroidal vessels, the virtual subchoroidal space expands and may cause expulsion of tissue from the eye (Figs. 9.14a). The degree of the expulsion depends on the point in the process at which the operator is able to effect wound closure.

The rate of the prolapse, the necessary speed of the operator's response, and the necessary quality of the wound closure depend on the pressure in the subchoroidal space, and thus on the pressure in the bleeding vessel (arterial or venous).

The surgeon directs his efforts toward *raising the intraocular pressure* above the pressure level in the subchoroidal space and maintaining that pressure until the pressure in the subchoroidal space can be lowered. Any measure that lowers the intraocular pressure beforehand (e.g., intrabulbar vitrectomy) will intensify the choroidal hemorrhage and worsen the situation.

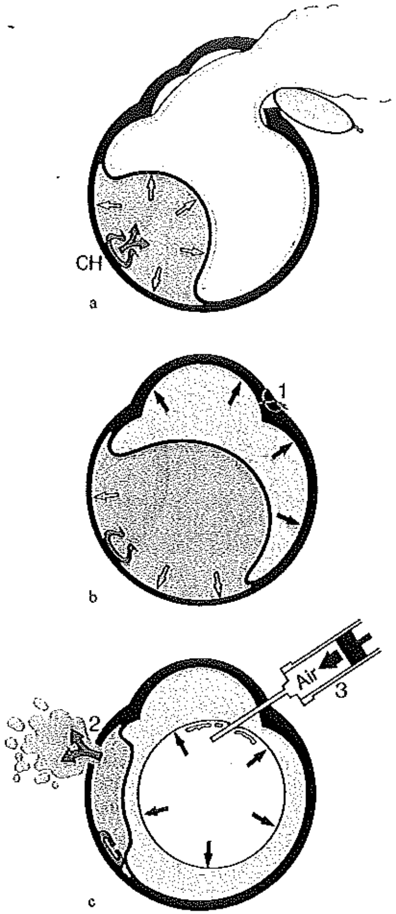

Fig. 9.14. Management of expulsive hemorrhage

a Mechanism of expulsive hemorrhage: Rupture of a choroidal artery (*CH*) allows extravasation into the subchoroidal space, the pressure in this space rising to the pressure of the arterial blood. The pressure in the open globe being lower, the newly created subchoroidal chamber can expand and expel the ocular contents out through the wound.

b Initial phase of management (*1*): Restoration of the intraocular pressure chamber. The outflow resistance from the anterior chamber is increased by performing a watertight wound closure. This allows the intraocular pressure to rise again to the level of the arterial pressure, arresting the hemorrhage.

c Phase two (*2*): Evacuation of the subchoroidal chamber through a sclerotomy. Phase three (*3*): The intraocular pressure must be kept high to avoid further extravasation from the damaged vessel. This is done by implanting an artificial pressure chamber in the form of an air bubble

The first step is to increase the outflow resistance from the vitreous chamber by effecting a secure **wound closure** (Fig. 9.14b)[13]. The second step is to lower the outflow resistance from the subchoroidal space by **incision of the sclera**. The third step is to raise the pressure in the vitreous space to evacuate the opened subchoroidal chamber. This is accomplished by **injecting air** as an *artificial pressure chamber* (Fig. 9.14c). The injection is continued (or repeated with each step) so that the total intraocular pressure during all maneuvers remains higher than the pressure in the leaking vessel.

Once the pressure in the subchoroidal space definitively has been brought to atmospheric, the initial incision may be reopened for reforming the anterior segment (anterior vitrectomy, repositioning of the iris, etc.).

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[13] The urgency of the intervention for arterial hemorrhage makes it advisable to preplace sutures for all intraocular procedures. These *safety sutures* will allow for rapid wound closure, provided they are strong enough to withstand the arterial pressure.

10 Future Trends

The ultimate goal of medicine is to make itself obsolete through its own development. Similarly, we may say that the goal of the eye surgeon is to develop methods which make the knowledge conveyed in this book unnecessary. And indeed, this development is well underway.

Our analysis of manipulations in *Eye Surgery* makes it plain where the key issues lie. The main problems in present-day ophthalmic surgery are the tissue deformations and displacements that are caused by surgical manipulations. These phenomena lead to discrepancies between the results that the surgeon would expect from his maneuvers and the results he achieves in the tissue. Consequently, the deformations and displacements that attend surgical actions must be anticipated and incorporated into the plan of operation. A large part of this book is concerned with such problems.

The deformations associated with *cutting* result from resistances and could be avoided by dividing tissues with ultrasharp instruments that cause no tissue displacement. Such instruments – weightless, ultrasharp, and practically without volume – are lasers, which are currently under development. The *uniting* of tissues can be accomplished without deformation as soon as a fast-setting, biologically compatible tissue adhesive becomes available. The *displacement* of tissues to assist manipulations can be avoided by applying the instrument directly to the intended site of action. Suitable microinstruments are already available and are being continually improved. *Visual monitoring* of the action will be greatly simplified once we are able to visualize previously invisible portions of the eye by endoscopic techniques. Finally, *spatial tactics* will be simplified when viscoelastic materials are made available in various grades of viscosity and elasticity. Volume stabilization could be achieved with these materials even under the action of large opposing forces.

As developments continue, it is certain that the eye surgery of the future will be vastly different from that known today. All who play a role in this development will one day note with satisfaction that it was fascinating to have been part of it.
