SUPPORTED COMPLEX AND HIGH RISK CORONARY ANGIOPLASTY

EDITED BY FAYAZ A. SHAWL, M.D., FACC

Director, Interventional Cardiology
Washington Adventist Hospital, Takoma Park, Maryland
Clinical Associate Professor of Medicine (Cardiology)
George Washington University School of Medicine, Washington, D.C.

SPRINGER-SCIENCE+BUSINESS MEDIA, B.V.

Library of Congress Cataloging-in-Publication Data

Supported complex and high risk coronary angloplasty/Fayaz A. Shawl (editor).
p. cm. — (Interventional cardiology; INCA 001)
Includes index.
ISBN 978-1-4613-6735-2 ISBN 978-1-4615-3890-5 (eBook)
DOI 10.1007/978-1-4615-3890-5

1. Transluminal angioplasty. 2. Cardiopulmonary bypass.
3. Therapeutics, Surgical. I. Shawl, Fayaz A. II. Series.
[DNLM: 1. Angioplasty, Transluminal, Percutaneous Coronary.
2. Cardiopulmonary Bypass. 3. Coronary Disease — therapy. 4. Risk Factors.
WG 300 S959]
RD598.S836 1991
617.4'12059 — dc20
DNLM/DLC
for Library of Congress 91-7004
CIP

DEDICATION

I would like to dedicate this book to the memory of my late father, Mohammad Saleem Shawl.

CONTENTS

CONTRIBUTING AUTHORS

Michael J. Domanski, M.D., F.A.C.C.
Senior Staff Cardiologist
National Heart Lung and Blood Institute
National Institutes of Health
Clinical Assistant Professor of Medicine
U.S.U. School of Medicine
Bethesda, MD 20892

Stephen G. Ellis, M.D., F.A.C.C.
Assistant Professor of Medicine
Assistant Director, Cardiac Catheterization Laboratory
The University of Michigan Medical Center
Ann Arbor, MI 48109-0022

David P. Faxon, M.D., F.A.C.C.
Director, Division of Cardiology
Boston University Medical Center
Boston, MA 02118

Alice K. Jacobs, M.D., F.A.C.C.
Director, Cardiac Catheterization Laboratory
Section of Cardiology
Boston University Medical Center
Boston, MA 02118

George A. Justison, B.S., C.C.P.
Chief Perfusionist
William Beaumont Hospital
Royal Oak, MI 48072

Sheila Kar, M.D., F.A.C.C.
Research Scientist
Division of Cardiology
Department of Medicine
Cedar Sinai Medical Center
Los Angeles, CA 90048

A. Kenneth Litzie, B.A., C.P.
Director, Mechanical Assist Division
PSICOR, Inc.
San Diego, CA 92127

E. Magnus Ohman, M.D.
Coordinator of Clinical Trials
Interventional Cardiology
Duke University Medical Center
Durham, NC 27710

Raymond A. Riehle
Clinical Trials Coordinator
Nimbus, Incorporated
Rancho Cordova, CA 95670

James A. Ronan J., M.D., F.A.C.C.
Clinical Professor of Medicine (Cardiology)
Georgetown University School of Medicine
Co-Director, Department of Cardiology
Washington Adventist Hospital
Takoma Park, MD 20912

Fayaz A. Shawl, M.D., F.A.C.C.
Clinical Associate Professor of Medicine (Cardiology)
George Washington University School of Medicine
Director, Interventional Cardiology
Washington Adventist Hospital
Takoma Park, MD 20912

Richard S. Stack, M.D., F.A.C.C.
Associate Professor of Medicine (Cardiology)
Director, Interventional Cardiology Program
Duke University Medical Center
Durham, NC 27710

Alan N. Tenaglia, M.D.
Cardiology Fellow
Duke University Medical Center
Durham, NC 27710

Richard K. Wampler, M.D., F.A.C.C.
Director, Medical Affairs
Nimbus Incorporated
Rancho Cordova, CA 95670

Marc H. Wish, M.D., F.A.C.C.
Assistant Clinical Professor of Medicine
Georgetown School of Medicine
Staff Cardiologist
Prince George's Hospital Center
Cheverly, MD 20785

Daniel Wohlgelernter, M.D., F.A.C.C.
Consulting Cardiologist
St. John's Hospital
Santa Monica, CA 90404

ACKNOWLEDGMENTS

The effort and challenge involved in putting this book together was far greater than ever anticipated, and its completion was made possible by the excellent work of my highly talented contributors. I am especially indebted for their very timely submission of state-of-the-art manuscripts.

I would like to offer my deepest appreciation to my friend and colleague, Dr. Michael J. Domanski, without whose help this volume would not have been possible. A special acknowledgement must be reserved for Mrs. Grace Murtagh, for her extraordinary secretarial support. I am deeply appreciative of my associates, Dr. Marc H. Wish, Dr. Tomas Hernandez, and Dr. Sudhakar Punja, for their profound support. I would also like to thank my cath lab personnel for helping me to develop the percutaneous technique for the institution of cardiopulmonary bypass support.

I am deeply grateful to my sons, David and Jonathan, for their understanding of the time necessary to make this book a reality. Finally, I would like to offer special thanks to Mr. Jeffrey Smith, Director of Kluwer Academic Publishers, for the publication of this volume.

Fayaz A. Shawl, M.D.

FOREWORD

Interventional cardiology is a creative, innovative, and rapidly advancing frontier of cardiology. There has been mind-boggling proliferation of technology in this field, the use of which requires extraordinary skills and know-how. In order to keep pace with the innovative genius of interventional cardiologists, it is indeed desirable to have specialty issues updating us on technology-orientated therapeutic procedures.

Contemporary interventional cardiology care is a highly specialized art, dependent on critical decision making, selection of the most appropriate interventional procedure, and the operator possessing extraordinary skills and compassion.

This first volume of the new series, *Supported Complex and High Risk Coronary Angioplasty*, attests to the preceding statement. Dr. Fayaz Shawl has mastered the procedure and has been very thoughtful and innovative in the clinical application of the percutaneous cardiopulmonary bypass support technique. This book provides to an interventionist the basic principles of cardiopulmonary bypass, identification of the high risk coronary angioplasty patient, and other alternate support devices for myocardial protection. Dr. Shawl and his team of talented contributors are to be complimented for providing us with this impressive volume on high technology.

There will be ongoing specialty issues in this series highlighting the developments, complications, and advances in interventional cardiology.

PREFACE

The practice of cardiology has changed dramatically since the introduction of percutaneous transluminal coronary angioplasty. The indications for coronary angioplasty are evolving from the classical single-vessel proximal, concentric, noncalcified subtotal obstruction to the very high risk patients, including those deemed inoperable. The evolving changes reflect the expanding horizons in the technology-oriented therapeutic alternatives and the blossoming of innovative, sophisticated technologies. Catheter-based interventional cardiology has gained widespread acceptance and its applications in a significant number of patients attests to its safety and feasibility. It appears the balloon and the wire can tackle any anatomic lesions or location, but can cause hemodynamic collapse if coronary angioplasty is performed in high risk patients. Such patients generally have severely depressed left ventricular function and/or only one remaining patent vessel or a target vessel that supplies greater than one half of the remaining viable myocardium. In such cases, an abrupt closure may spell hemodynamic crisis with imminent death.

To make the procedure safe and fessible, and to reduce the prohibitive risk of the procedure, an innovative technology has emerged from the operating room. This is the development of percutaneous cardiopulmonary bypass support (PCPS), which can circumvent the potential problems of the high risk procedure, provide hemodynamic support, and facilitate emergency coronary angioplasty, even in the most high risk patients. In addition, early institution of PCPS can stabilize patients who suffer cardiac arrest in the catheterization

laboratory, as well as facilitate coronary angioplasty or transfer to the operating room for coronary bypass graft surgery.

This is a specialized procedure and hence this book is intended to provide detailed information on all aspects of the procedure and potential procedure-related risks and complications. I must caution that decisions about the selection of complex cases and the strategy for the complete procedure should be made in concert with the referring physician, cardiac surgical team, and interventional team. Analysis of many complex factors must be taken into account before embarking on this path of salvaging myocardium and life.

The complete procedure, which includes insertion and operation of PCPS, performance of coronary angioplasty, and termination of bypass, is indeed a complex and multifaceted technique. Extraordinary skills and well-thought-out management strategy will enhance the success and safety of the procedure. The basic priniciples of cardiopulmonary bypass physiology will be discussed, and an approach to supported angioplasty in high risk patients will be developed. The results of cardiopulmonary bypass supported interventions will be discussed.

This book also attempts to describe the most up-to-date technology of various other support devices, which may be beneficial in supporting certain subgroups of patients undergoing high risk coronary intervention. Present prospects and future developments will be explored with an innovative bend.

Fayaz A. Shawl
Editor

SECTION I

1. IDENTIFICATION OF THE HIGH RISK ANGIOPLASTY PATIENT

STEPHEN G. ELLIS

INTRODUCTION

A recognition and understanding of the factors that make a patient truly at high risk for unsupported coronary angioplasty (PTCA) are necessary for the proper implementation of supported PTCA or an avoidance of the technique of PTCA altogether.

The likelihood of procedure-related *infarction* is a function of the probability of abrupt coronary artery closure that cannot be satisfactorily treated by repeat dilatation, placement of a perfusion catheter, or restoration of adequate coronary flow by an advanced technique, such as intracoronary stenting or laser balloon angioplasty. The likelihood of procedure-related *death* is the product of the likelihood of untreatable abrupt closure multiplied by the probability of dying once an untreated coronary obstruction has occurred.

The factors predictive of abrupt closure, closure-related death, and the likelihood of successfully treating abrupt closure are reasonably well understood, and hence a rational approach to the management of the high risk angioplasty patient is possible.

FACTORS PREDISPOSING TO ABRUPT CORONARY CLOSURE DURING PTCA

Clinical factors

Multiple clinical variables have been identified that appear to heighten the risk of acute ischemic complications during or immediately after coronary angi-

oplasty. Patients with unstable angina [1–9], the elderly [1,10–16], and possibly females [17] (although this is controversial [18–20]), form the clinical substrate in which complications are more likely. A difficulty in the interpretation of many publications analyzing this question is their use of small sample sizes and univariate analyses without regard to other factors likely to influence outcome [21]. Multivariate analysis of larger patient series is more appropriate and less likely to be misleading, although the testing of multiple variables may lead to type II statistical errors [21]. Appropriate multivariate testing has suggested that angiographic variables have greater predictive power in this setting than do clinical variables [17,22].

The term *unstable angina* has been used to describe a wide constellation of findings with correspondingly variable prognoses [23–25]. Medical treatment, including antiplatelet and antithrombotic agents, greatly lessens the risk of refractory ischemia or infarction in the short term [26]. DeFeyter and others [2–9] have emphasized that, even with current pharmacologic protection, PTCA-related major complications occur in 3–12% of patients with unstable angina, and suggest that this occurs because of the thrombi that are frequently present [27]. It is tempting to suggest, because of the overall good short-term prognosis of these patients with medical therapy [26] and because associated thrombus may be shown to often resolve with intravenous heparin administration [28], that catheterization and angioplasty should be deferred for 1–2 weeks if possible. However, this would be a costly practice and the rate of resolution of risk with this strategy is unknown. Early catheterization with concomitant use of thrombolytic agents has also been suggested [29–32]. More powerful antiplatelet agents, such as monoclonal antibodies directed against the platelet glycoprotein receptors [33,34], may also be able to lessen the risk of PTCA in these patients. This approach is currently being tested.

Acute ischemic events complicating elective angioplasty in the elderly ($\geq$80 years) have been reported by experienced groups to occur in 5–19% of patients, a rate considerably higher than reported with younger patients [11,12]. The reason for this high risk is probably multifactorial and may include the higher incidence of calcified and diffusely diseased arteries and stenoses [16], as well as perhaps a higher incidence of unstable angina [11]. The incidence of acute ischemic complications in carefully chosen patients 70–79 years of age is probably more nearly similar to those of younger patients [10–14]. Fatal outcome (q.v.) with PTCA in the patients older than 65–70 years is much more common than in younger patients, however [10–14].

Considerable controversy has arisen as to whether or not females are at greater risk of acute ischemic complications with PTCA than are males. An increase in risk was first suggested by the 1979–83 NHLBI Registry [35] and was seemingly confirmed by the large Emory experience reported in 1988 [17]. However, in the more recent NHLBI Registry, female gender was not an independent predictor of risk, but rather was associated with other high risk

variables (advanced age, diabetes, and unstable angina) [19]. These findings were supported by recent reviews from the Cleveland Clinic [18] and Boston's Beth Israel Hospital [20].

Anatomic factors

Coronary angiography provides the best currently available preprocedural assessment of the risk of PTCA [17] and allows for a stratification of patients into low, medium, and high risk groups for complications [17,22]. Analyses of complications when less-sophisticated angioplasty equipment was used (fixed guidewire, high profile) found right coronary artery attempts [35], greater lesion severity [35], lesion eccentricity [35], long lesions [35], and diffuse disease [35] to increase risk. More recent series investigating multiple clinical and angiographic variables have found that longer lesions, stenoses at end-diastolic bends $\geq 45°$, bifurcations, apparent thrombus, diffuse disease, and multivessel disease each impart a greater risk [17,22]. Right coronary artery attempts and high-grade stenoses no longer appeared to heighten risk, whereas lesion eccentricity only minimally increased risk [17,22]. There appears to be an additive effect of each factor on risk such that a modification of the ACC/AHA stenosis classification system [36] (Figure 1-1), wherein class B stenoses were divided into those with only one adverse characteristic (type B1) and those with two or more characteristics (type B2), was the most powerful predictor of adverse outcome in the most recent large and comprehensive analysis of this problem [22]. This large analyses suggested that in patients with multivessel disease, one could expect a 1–2% incidence of major complications with type A stenoses, a 4% incidence with type B1 stenoses, a 10% incidence with type B2 stenoses, and a >20% incidence with type C stenoses. The only clinical variable giving further prognostic information beyond that provided by this classification was the presence of diabetes.

It must be recognized, however, that there are limitations to this angiography-based statistical approach to patient stratification. Due to the generally low risk of complications in patients selected for angioplasty and the absence of extremely powerful correlates of risk, the predictive value of these schema for outcome in an individual patient is somewhat limited (multiple $r^2 < 0.20$ [17,22]). That is to say, even for a high risk type C stenosis, the likelihood of avoiding complications may approach 80%, and 10–15% of patients having major ischemic complications will have none of the recognized risk factors [17,22]. It is hoped that the addition of techniques such as angioscopy [27] and intravascular ultrasound [37] will improve our ability to predict outcome, but demonstration of their efficacy in large enough patient numbers to develop risk stratification schema is probably several years away.

Several other rarer anatomic situations have been identified that increase the risk of PTCA. Topol et al. reported a 9.5% need for emergency bypass surgery in patients undergoing dilatation of right coronary artery ostial stenoses and ascribed the increased complication rate to direct trauma of the guiding

Lesion Specific Characteristics	
Type A Lesions (high success, low risk)	
• Discrete (<10 mm length)	• Little or no calcification
• Concentric	• Less than totally occlusive
• Readily accessible	• Non ostial in location
• Nonangulated segment, <45°	• No major branch involvement
• Smooth contour	• Absence of thrombus
Type B Lesions (moderate success, moderate risk)	
• Tubular (10 to 20 mm length)	• Moderate to heavy calcification
• Eccentric	• Total occlusions <3 months old
• Moderate tortuosity of proximal segment	• Ostial in location
• Moderately angulated segment, >45°, <90°	• Bifurcation lesions requiring double guide wires
• Irregular contour	• Some thrombus present
Type C Lesions (low success, high risk)	
• Diffuse (>2 cm length)	• Total occlusions >3 months old
• Excessive tortuosity of proximal segment	• Inability to protect major side branches
• Extremely angulated segments >90°	• Degenerated vein grafts with friable lesions
Type B1 lesions have only 1 adverse characteristic, while type B2 lesions have ≥ 2 adverse characteristics from within those described under "Type B Lesions"	

Figure 1-1.

catheter on the freshly dilated stenosis, increased need for guide catheter manipulation (standard Judkins configuration catheters often provide insufficient backup in this setting, and catheters commonly need to be partially withdrawn for balloon inflation), and to the frequent requirement of high balloon pressures to open the stenoses [38]. Diffusely diseased saphenous vein bypass grafts also pose a higher risk of complications [39], although PTCA in carefully chosen graft stenoses carries a low risk and a high primary success rate [39–43]. Choice should not necessarily be made on the basis of the graft age, but rather the avoidance of long stenoses, or those with irregular edges or partial contrast retention that may indicate the presence of active thrombus [44]. Nonetheless, embolization of grumous or thrombus material of sufficient magnitude to cause infarction occurs in up to 10% of cases [39,44,45] and probably occurs as a subclinical event even more commonly. The risk of ischemic complications appears to be much less with dilatation of internal mammary arteries (IMA), probably because of their more focal atherosclerotic involvement [46–49]. The greatest risk in this setting may be with traumatic intubation of the often-fragile origin of the IMA, rather than with the balloon inflation itself. Finally, PTCA of chronic total occlusions, a situation in which it is often said that one "cannot make the situation any worse," is not always as risk free as it might appear. Andreae et al. recently reported on 333 such procedures, describing a 6% incidence of arterial closure, a 4% incidence of myocardial infarction, and a 2.4% need for emergency bypass surgery [50].

Derecruitment or embolization of collaterals have been postulated as mechanisms by which previously apparent collaterals beyond total occlusion become functionally insufficient following PTCA [50,51]. In addition, an often unsuspected risk involves left main or right ostial dissection due to the common need for maximal guide catheter backup and consequent manipulation in this setting.

Thus, a careful appreciation of the coronary anatomy in conjunction with important clinical characteristics should allow for prospective stratification of a patient's risk with angioplasty, thereby placing the benefit-risk ratio of PTCA in perspective compared with other management options. In many instances, this may be done at the time of catheterization, thus allowing for cost-saving immediate angioplasty during the same procedure. In relatively "straightforward" situations, this can be done without any increase in risk to the patient [52]. However, if, for whatever reason, image quality is not optimal, or if the lesion is not particularly advantageous for angioplasty, it is more prudent to develop the angiograms and carefully consider the therapeutic options. Finally, if supported angioplasty is considered a possible treatment option, distal aortography with iliofemoral panning should be obtained as part of the diagnostic procedure.

Pharmacologic factors

While it is not presently possible to pharmacologically modify the risk of balloon-inflation-induced intimal and medial disruption, chemical modification of the platelet-fibrin response to vascular injury is possible and clearly influences the outcome of the procedure.

Recently, Schwartz [53], White [54], and Chesebro [55] independently reported the beneficial effect of antiplatelet agents in the setting of elective angioplasty demonstrated from randomized trials. Thus, it is clear that elective coronary angioplasty should not be performed without prior antiplatelet therapy. The questions of the optimal dose of aspirin and the additional need for dipyridamole have been addressed by the Emory group in randomized trials. Mufson [56] reported no difference in the likelihood of ischemic complications between patients randomized to 80 mg or 1500 mg of aspirin daily starting the day prior to the procedure. Lembo [57] found that the addition of dipyridamole 75 mg t.i.d. did not alter the incidence of ischemic complications compared with aspirin at a dose of 325 mg t.i.d. Anecdotal and pharmokinetic evidence suggests that the administration of a single aspirin tablet prior to angioplasty does not reliably reduce the risk of platelet-associated complications [58,59]. Furthermore, even apparently adequate dosages of aspirin may provide inadequate benefit when they are administered with other drugs that alter their absorption, such as antacids or H_2-receptor blocking agents [60].

Dextran, which has some antiplatelet effect, was commonly used during PTCA prior to 1984 when a study by Swanson and the Mayo Clinic group suggested no efficacy of this agent [61]. However, in that study dextran was

administered beginning 30 minutes prior to dilatation, and several studies have shown that the maximal effect of dextran on platelet adhesion does not occur until 4–6 hours of infusion [62,63]. Thus the effect of optimal administration of dextran in this setting is unknown. Coronary spasm and major anaphylactic reactions, such as profound hypotension, however, have rarely been reported following dextran infusion [64], and the routine use of this agent cannot be advocated.

More powerful antiplatelet agents, including monoclonal antibodies directed against the glycoprotein receptors that mediate platelet adhesion and aggregation, may soon be clinically available [34]. One of these, a murine monoclonal antibody that binds to the glycoprotein IIb/IIIa receptor that mediates aggregation, eliminated thrombus formation in 7 of 7 dog coronaries undergoing PTCA, compared with 1 of 7 pretreated with aspirin [33]. The safety of this antibody in angioplasty patients is currently being tested at the University of Michigan and Duke University.

Prolonged heparin infusion, which decreases fibrin deposition at sites of arterial injury [65] and has both inhibitory [66] and activating effects on platelets [67,68], appears to be useful in high risk patients. In low risk patients, however, prolonged heparin infusion appears not to be needed and may in fact increase bleeding complications. Ellis et al. [69] randomized 416 low risk patients (patients with a large dissection, post-PTCA filling defect, or "suboptimal result" were excluded) to 18- to 24-hour post-procedural heparin versus dextrose and found no difference in the incidence of ischemic complications (1.8% with heparin compared with 2.4% with dextrose). The group receiving heparin had a somewhat higher incidence of bleeding (9% versus 5%, $p = 0.09$). Indirect evidence, such as nonrandomized findings of a lower incidence of complications in patients with unstable angina pretreated with heparin [70] and reports of a close temporal relation of coronary occlusion to the discontinuation of anticoagulation following PTCA [71], support the use of prolonged heparinization following PTCA in high risk patients. Importantly, patient response to heparin is highly variable, and the standard 10,000 U bolus may give activated clotting time (ACT) levels <300 seconds (which has been associated with thrombus formation) in 5% of patients with stable angina and up to 15% of patients with unstable angina [72]. Intraprocedural heparin surveillance can be rapidly achieved with bedside ACT evaluation. Thus, closely monitored and possibly prolonged heparin is probably useful in patients with unstable angina or a less than optimal post-PTCA result.

Finally, the use of nitrates, calcium-channel blockers, beta blockers, and flurocarbon emulsions [73,74] has been advocated to allow longer balloon inflation with less ischemia. A benefit from the relatively brief augmentation of balloon-inflation duration allowed by these agents appears unlikely. Nitrates may provide an additional antiplatelet effect [75], and of course, nitrates and calcium-channel blockers may prevent the occasionally important coronary spasm seen in this setting [76,77].

In summary, proper administration of aspirin or other equivalent antiplatelet agents is required to reduce thrombotic complications of coronary angioplasty to a minimum, and prolonged postprocedural heparinization may be useful in high risk patients. Nitrates and calcium-channel blockers are helpful in the management of occasionally important coronary spasm, but the routine use of other cardioactive medications is probably not needed.

Estimation of likelihood of successful treatment of major acute complications

An assessment of the likelihood of successful treatment of PTCA-induced ischemia is an integral part of the assessment of the overall procedural risk. Percutaneous cardiopulmonary bypass may facilitate the treatment of ischemia, because the hemodynamic consequences of ischemia are minimized. However, this support does not provide coronary perfusion or adequately unload the left ventricle, and hence timely treatment is still imperative.

The most common causes of prolonged ischemia during PTCA are, in approximate order of frequency, a) coronary dissection, b) intracoronary thrombus formation, c) guide or balloon catheter damping, and d) coronary spasm. The last two causes are often not predictable, but fortunately are usually readily identifiable and treatable with catheter withdrawal and intracoronary nitroglycerin or rarely sublingual nifedipine, respectively.

With dissection, repeat dilatation with long inflations, perhaps best with low inflation pressure and slightly oversized balloons, can obtain an adequate result and obviate the need for bypass surgery in 44–85% of coronary occlusions [78–80]. Ten- to 20-minute inflations using a perfusion balloon succeed in 50–60% of patients in "tacking up" and stabilizing a tear after 4-minute inflations have failed [81]. Repeated reclosure after prolonged balloon inflation should prompt placement of a bailout catheter [82–84] if the patient is a surgical candidate. Importantly, due to the relative stiffness and poor profile of these systems, solid guide catheter support and a minimum of vessel tortuosity from the ostium to beyond the stenosis are required for placement. To a certain extent, this can be judged beforehand.

In the near future, newer technologies, such as intracoronary stenting [85], laser balloon angioplasty [86], and directional atherectomy [87], may become widely available as treatment modalities for dissection-mediated abrupt coronary closure. The delivery systems for these technologies are currently undergoing a rapid evolution, so it is difficult to address the question of the likelihood of successful placement of such a device to a given disrupted coronary segment. Currently, all three systems are somewhat bulky, and the aforementioned concerns relating to the perfusion balloon and bailout catheters will likely apply. Of the three technologies, stenting appears perhaps most promising, although randomized trials and consideration of changing technologies makes a comparative evaluation difficult. It is likely that 80–90% of small- or moderate-size proximal dissections will be able to be successfully

Table 1-1. Assessment of risk of major ischemic complications

ACC/AHA stenosis type	No bailout treatment expected	Bailout treatment expected	Advanced technologies expected
No diabetes mellitus (% risk)			
A	2	1	<1
B1	3	2	1
B2	8	4	2
C	16	8	3
Diabetes present (% risk)			
A	4	2	1
B1	6	3	1
B2	16	8	3
C	30	15	6

Modified from References 22, 81, and 85.

treated with one or more of these newer techniques, providing that the device itself can be advanced to the point of dissection.

Thrombus may prove more difficult to treat, although Cohen recently reported that low doses of intracoronary urokinase (100,000–250,000 U) followed by several days of heparin therapy may salvage up to 79% of closures [88]. In the author's experience, thrombus propagation after angioplasty in the setting of early (5–14 days) post-myocardial infarction angina may be especially refractory to treatment, occasionally failing to resolve with systemic doses (1.5–2 million U) of intravenous urokinase.

If early indication of successful reperfusion is not seen and more than a minor myocardial infarction is felt likely to ensure, the operator should not hesitate in calling the surgeons for urgent bypass surgery, provided that is a possibility. Although surgical results in this setting will be discussed in a later section of this chapter, they vary widely depending on the experience of the angioplasty operator and the surgical team. Even experienced surgeons find it difficult to use internal mammary arteries as conduits in this setting, however. The Emory team recently reported the use of internal mammary arteries after failed angioplasty in only 26% of cases [89]. This should be considered when the relative merits of PTCA, supported or otherwise, and elective bypass surgery are weighed.

A quick reference to the expected likelihood of major ischemic complications is presented in Table 1-1.

Factors affecting the risk of death with acute closure

Several recent large-scale studies have addressed the issue of assessing the likelihood of death in patients undergoing elective PTCA. Ellis et al. [90] analyzed over 8000 procedures from Emory University Hospital and the San Francisco Heart Institute performed between 1980 and 1986, and found female gender, multivessel disease, collaterals emanating from beyond the site dilated,

and a large potentially ischemic coronary bed to independently predict an adverse outcome after abrupt closure. Holmes et al. [1], reporting from the 1800-patient 1985–86 NHLBI PTCA Registry, found that a history of congestive heart failure, age ≥65 years, triple-vessel or left main coronary disease, and female gender each predicted a higher likelihood of death. Finally, Park et al., reporting from the over 5000-case experience accrued at the Mid-America Heart Institute by 1987, found left ventricular ejection fraction <30%, age >70 years, multivessel disease, and unstable angina to independently predict death [91]. The Emory-San Francisco Heart Institute study has recently been updated and has included recent University of Michigan data such that over 12,000 more recently performed procedures have now been analyzed (unpublished data).

The importance of left ventricular function prior to and after induced ischemia is intuitive and is supported by all three studies. Cardiogenic shock is common when ≥40% of the left ventricular myocardium ceases acutely to function [92]. Importantly, in the Emory-San Francisco Heart Institute study, left ventricular ejection fraction prior to PTCA was not a predictor of mortality. Rather, a measure of the amount of ischemic myocardium present after PTCA, the jeopardy score [90], was strongly predictive of outcome ($p = 0.003$). The amount of potentially ischemic myocardium may not always be easy to access or quantify, but the relatively crude jeopardy score (Figure 1-2) has been shown to be useful [90]. In this scoring system, the coronary tree is divided into six territories based on necropsy studies of Kalbfleisch [93] and others who evaluated the amount of myocardium subserved by each of the major coronary arteries: a) the proximal left anterior descending coronary artery, b) by the mid and distal left anterior descending coronary artery, c) by the major diagonal branches, d) by the proximal circumflex and obtuse marginal system, e) the posterolateral branches of the right or circumflex coronary arteries, and f) the posterior descending coronary artery [6]. By taking the sum of the areas that are akinetic (one point for each area), or hypokinetic ($\frac{1}{2}$ point for each area), and those likely to become akinetic in the event of abrupt closure (including those subserved by ≥70% stenosis, and therefore to become hypoperfused in the event of hypotension), the risk of abrupt closure-induced death without cardiopulmonary support can be assessed (Table 1-2). Scoring systems that assessed only pre-PTCA akinesis and hypokinesis, without assuming a deterioration of function in areas subserved by arteries that closed or were measured by calipers ≥70% narrowed (corresponding to approximately 85–90% stenosis assessed visually), were less predictive (Table 1-3).

The risk of coronary angioplasty was perhaps first noted to be higher in women than in men in the first NHLBI Registry [35]. It has been suggested that this might have been a result of the early common use of 3.0-mm balloons, which were sometimes oversized for women, thus predisposing them to acute closure and consequently a higher incidence of death. The first Emory-San Francisco Heart Institute analysis [90], however, suggested that

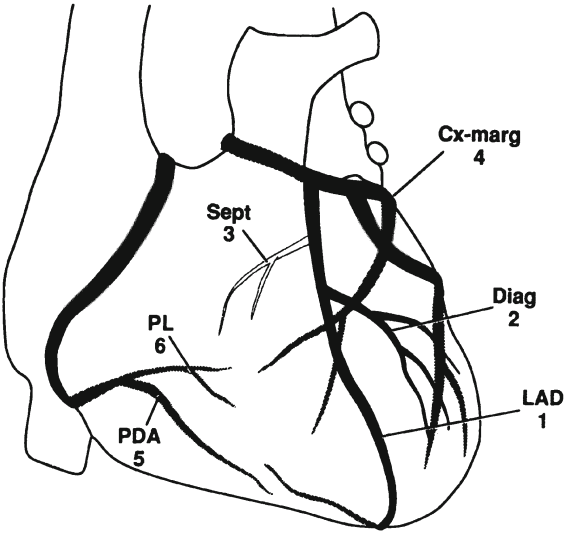

Figure 1-2. Diagram of a right dominant coronary artery tree showing the six coronary segments evaluated to assess the jeopardy score. In a left dominant system, the Cx-marg territory would be assigned 2 points and the RCA system assigned 1 point. For each of the six segments, 1 point is given if the corresponding regional ventricular contractility is akinetic, $\frac{1}{2}$ point is given if it is hypokinetic and 1 point is awarded if a ≥70% stenosis is present to "jeopardize" the territory (maximum of 1 point per segment, maximum 6 points total).

Table 1-2. Univariate predictors of death after acute vessel closure

	Patients who died no. (%)[1]	Patients who survived no. (%)[1]	p
Women	12 (92.3)	32 (32.0)	<0.0001
Collateral vessels from artery dilated	6 (50.0)	2 (2.4)	≤0.0001
Use of intraaortic balloon counterpulsation	8 (61.5)	16 (16.2)	0.0002
Hypotension (SBP ≤90) after initial coronary arteriography and nitroglycerin and/or nifedipine	6 (54.5)	2 (4.0)	0.0003
Hypotension (SBP ≤90) after acute closure	10 (83.3)	28 (28.6)	0.003
Overall jeopardy score ≥2.5	10 (76.9)	25 (31.3)	0.003
LVH by ECG	5 (38.5)	4 (7.4)	0.013
Hypertension (SBP >150) in catheterization laboratory before PTCA	8 (61.5)	16 (18.6)	0.022
Diabetes mellitus	5 (38.5)	11 (11.0)	0.024
Multivessel disease	10 (76.9)	40 (41.2)	0.034

[1] Percent of patients for whom variable was known.
SBP = systolic blood pressure.
Reproduced with permission of the American College of Cardiology [90].

Table 1-3. Logistic regression analysis of preprocedural risk factors for cardiac death after acute closure from 8207 total procedures

Variable	Coefficient	p value
Collateral vessels from beyond the site dilated	−1.256	0.0001
Women	−5.237	0.0014
Multivessel disease	−1.140	0.0020

Reproduced with permission of the American College of Cardiology [90].

other factors also predisposed women to an increased risk of death. The female patient's more frequent hypotensive responses to vasodilators [90] and the inverse correlation of body surface area with increased risk of death [90] suggest that they may be less well able to respond to the stress of abrupt vessel closure because of a volume depletion. The correlation of left ventricular hypertrophy with risk of death also supports this hypothesis, as patients with hypertrophy are more preload dependent. In addition, women have smaller coronary arteries than do men [94], and the coronary artery diameter of the women who died in the Emory series was somewhat smaller than that of women who did not have fatal complications. This suggests that the severity of disease may have been underestimated in these women, placing them at higher risk of ischemia and death. Finally, women may have a less well-conditioned left ventricle than do men, as reflected in their lower contractile reserve function [90]. Mortality in women undergoing coronary bypass surgery has also been found to be higher than that for men undergoing the same procedure [95,96].

Age >65–70 years was also an independent predictor of mortality in both the NHLBI [1] and in the Mid-American Heart Institute series [91], as it has been in most surgical series [95–97]. Although it is inappropriate to equate physiologic with chronologic age, patients ≥80 years of age appear to be at particularly high risk with abrupt closure from PTCA [11,12].

The most recent Emory—San Francisco Heart Institute—University of Michigan review provides further insight into the risk and mechanisms of death with elective angioplasty, the latter having particular importance in determining the potential utility of support devices intended to limit procedural mortality. In 12,016 consecutive procedures, abrupt closure of the dilated artery(ies) occurred in 459 patients (3.8%), and of these, 27 died (0.2%). Three primary mechanisms of death were identified as follows: a) *left ventricular dysfunction consequent to closure of the dilated artery* (n = 14, 52%). The risk of this occurring was directly related to the risk of the individual stenosis closing [22] and to the jeopardy score [90] (see Tables 1-1 and 1-4 and Figure 1-2). Thus, patients at highest risk for this process can be identified, and furthermore, their identification may allow for prophylactic placement of support devices [98–100] to facilitate emergency treatment of life-threatening

Table 1-4. Relation of jeopardy score to cardiac mortality in patients with abrupt arterial closure

Jeopardy score	Mortality (%)
0.0–2.0	2.3
2.1–3.0	10.0
3.1–5.0	11.5
5.1–6.0	33.3

From analysis of 12,016 procedures by Ellis et al., unpublished observations.

ischemia. b) *Right ventricular dysfunction due to proximal right coronary artery occlusion* (n = 5, 18%). This process was related only to the risk of closure of the proximal right coronary artery stenosis and not to the jeopardy score. It is particularly difficult to treat because of the general lack of available and effective right ventricular assist devices and because indirect perfusion devices (coronary sinus retroperfusion [100]) do not perfuse the right ventricle. This inability to effectively manage ischemia from this site may make high-risk proximal right coronary artery stenoses more lethal in the era of supported angioplasty than any other coronary site. c) *Left ventricular dysfunction consequent to guide-catheter-induced left main coronary dissection* (n = 4, 15%). This infrequent and difficult to predict complication accounted for 15% of all cardiac deaths in this series. Because its occurrence is rare and not easily predictable, prophylactic support is of no value. However, the ability to "crash on" cardiopulmonary support in this setting may be life saving. A recent case from our laboratory illustrates this point. A 62-year-old male, 7 days after an uncomplicated inferior infarct treated with thrombolytic therapy, was referred for diagnostic angiography. A subtotal right coronary artery stenosis, potentially suitable for PTCA, was first documented. Initial injection of the left coronary system resulted in a large and partially occlusive dissection of the left main coronary artery. The remainder of the left coronary system was free of apparent disease. The patient's systolic blood pressure rapidly fell to 55 mmHg, and global ST segment elevation was noted in the monitored ECG leads. Fluid and pressor administration augmented the systolic pressure to only 60 mmHg. The cardiopulmonary support (CPS) team, which was nearby for another potential procedure, was called. An attempt to cross and perfuse the left main was attempted as the contralateral groin was prepared for CPS instrumentation, but was unsuccessful and the patient developed an agonal rhythm. The patient was placed on full bypass support within 15 minutes of the initial insult, was taken for emergency bypass surgery with stable hemodynamics and a mean arterial pressure of 68 mmHg, and left the hospital 8 days later with only minimum anterolateral hypokinesis by echocardiography. The immediate availability of CPS equipment and personnel trained in its use was life saving in this case and may perhaps decrease mortality from routine

elective cath lab procedures by up to 50% (author's estimation). The remaining four deaths resulted from multisystem failure in patients who had undergone otherwise uncomplicated emergency bypass surgery. The role of Cardiopulmonary bypass support in high risk interventions is fully described by Shawl in Chapters 6–9.

CONCLUSIONS

Thus, the risk of cardiac death is predictably high in the presence of a large amount of ischemic and nonfunctional left ventricular myocardium, in the very elderly, and quite probably in females. An estimate of this risk can be made from analyses derived from large numbers of patients undergoing PTCA (see Tables 1-1 and 1-4). Patients with a large amount of jeopardized myocardium, particularly if the lesions to be dilated are not low risk and are not expected to be easily accessible to percutaneous perfusion devices [98–100], may do better with bypass surgery or perhaps supported PTCA.

Deaths from left main and proximal right coronary artery occlusion, however, are less predictable and yet make up a substantial minority of deaths in large series. Their potential occurrence mandates the ready availability of cardiopulmonary support in all moderate- to high-volume cath labs and the development of improved right ventricular support devices, respectively.

These factors, as well as the risk of closure from the individual lesions to be dilated, the patient's risk with bypass surgery or other forms of revascularization, and the patient's need for any revascularization at all, need to be carefully considered prior to performing angioplasty.

ACKNOWLEDGMENTS

The author is deeply grateful for the expert secretarial assistance provided by Ms. Sheree Wilson.

REFERENCES

1. Holmes DR Jr., Holubkov R, Vlietstra RE, et al. Co-investigators of the National Heart, Lung, and Blood Institute Percutaneous Transluminal Coronary Angioplasty Registry. Comparison of complications during percutaneous transluminal coronary angioplasty from 1977 to 1981 and from 1985 to 1986: The National Heart, Lung and Blood Institute Percutaneous Transluminal Coronary Angioplasty Registry. *J Am Coll Cardiol* 1988; 12:1149–1155.
2. de Feyter PJ, Serruys PW, Wijns W, van den Brand M. Emergency PTCA in unstable angina pectoris refractory to optimal medical treatment. *N Engl J Med* 1985; 313:342–346.
3. de Feyter PJ, Serruys PW, Soward A, van den Brand M, Bos E, Hugenholtz PG. Coronary angioplasty for early postinfarction unstable angina. *Circulation* 1985; 74:1365–1370.
4. de Feyter PJ, Suryapranata H, Serruys PW, et al. Coronary angioplasty for unstable angina: Immediate and late results in 200 consecutive patients with identification of risk factors for unfavorable early and late outcome. *J Am Coll Cardiol* 1988; 12:324–333.
5. Gottlieb SO, Walford GD, Ouyang P, et al. Initial and late results of coronary angioplasty for early postinfarction unstable angina. *Cathet Cardiovasc Diag* 1987; 13:93–99.
6. Safian RD, Snyder LD, Synder BA, McKay RG, Lorell BH, Aroesty JM, Pasternak RC, Bradley AB, Monrad ES, Baim DS. Usefulness of percutaneous transluminal coronary angioplasty for unstable angina pectoris after non-Q-wave acute myocardial infarction. *Am J Cardiol* 1987; 59:263–266.

7. Black AJ, Brown CS, Feres F, Roubin GS, Douglas JS. Coronary angioplasty and the spectrum of unstable angina pectoris: What determines risk? (abstr). *Circulation* 1988; 78(Suppl. II):II-8.
8. Kamp O, Beatt KJ, de Feyter PJ, et al. Short-, medium-, and long-term follow-up after percutaneous transluminal coronary angioplasty for stable and unstable angina pectoris. *Am Heart J* 1989; 117:991–996.
9. Goldbaum T, DiSciascio G, Cowley MJ, Vetrovec GW. Early occlusion following successful coronary angioplasty: Clinical and angiographic observations. *Cathete Cardiovasc Diag* 1989; 17:22–27.
10. Simpfendorfer C, Raymond R, Schraider J, et al. Early and long-term results of percutaneous transluminal coronary angioplasty in patients 70 years of age and older with angina pectoris. *Am J Cardiol* 1988; 61:457–458.
11. Kern MJ, Deligonul U, Galan K, et al. Percutaneous transluminal coronary angioplasty in octogenarians. *Am J Cardiol* 1988; 61:457–458.
12. Good TH, Calkins M, Ligon R, McCallister BD, Hartzler GO. PTCA in the ultra-elderly (abstr). *Circulation* 1987; 76(Suppl. IV):IV-464.
13. Kelsey SF, Miller DP, Leatherman LL, Cowley MJ, NHLBI PTCA Registry Investigators. Coronary angioplasty in the elderly: 1985–1986 NHLBI PTCA Registry. *Circulation* 1988; 78(Suppl. II):II-283.
14. Lewin RF, Dorros G, Mathiak ML. Long term followup after successful coronary angioplasty in patients of age ⩾70 years (abstr). *J Am Coll Cardiol* 1988; 11:51.
15. Coca F, Fajadet J, Caster L, Marco J. Transluminal coronary angioplasty in the elderly (over 70 years old): Immediate and long term results (abstr). *Eur Heart J* 1987; 8(Suppl. II):220.
16. Imburgia M, King TR, Soffer AD, Rich MW, Krone RJ, Salimi A. Early results and long-term outcome of percutaneous transluminal coronary angioplasty in patients age 75 years or older. *Am J Cardiol* 1989; 1127–1129.
17. Ellis SG, Roubin GS, King SB, et al. Angiographic and clinical predictors of acute closure after native vessel coronary angioplasty. *Circulation* 1988; 77:372–379.
18. McEniery PT, Hollman J, Knezinek V, et al. Comparative safety and efficacy of percutaneous transluminal coronary angioplasty in men and in women. *Cathet Cardiovasc Diag* 1987; 13:364–371.
19. Kelsey SF, Cowley MJ, Costigan T, Detre KM, Passamani E, Robertson T. Results of PTCA in women in 1985 (abstr). *J Am Coll Cardiol* 1987; 9:56.
20. Lorell BH, McCabe CH, Sipperly ME, Baim DS. Women and PTCA: No feminine mystique. *Circulation* 1987; 76(Suppl. IV):IV-400.
21. Pocock SJ, Hughes MD, Lee RJ. Statistical problems in the reporting of clinical trials. *N Engl J Med* 1987; 317:426–432.
22. Ellis S, Cowley M, Vandormael M, Bulle T, DiSciascio G, and the MAPS Group. Risk of angioplasty in multivessel disease — improved assessment with modified ACC/AHA score. *Circulation*, submitted, 1990.
23. Conti CR, Brawley RK, Griffith LSC, et al. Unstable angina pectoris: Morbidity and mortality in 57 consecutive patients evaluated angiographically. *Am J Cardiol* 1973; 32:745–750.
24. Cairns JA, Fantus JG, Klassen GA. Unstable angina pectoris. *Am Heart J* 1976; 92:373–386.
25. Scanlon PJ. The intermediate coronary syndrome. *Prog Cardiovasc Dis* 1981; 23:351–364.
26. Theroux P, Ouimet H, McCans J, et al. Aspirin, heparin, or both to treat acute unstable angina. *N Engl J Med* 1988; 319:1105–1111.
27. Sherman CD, Litvack F, Grundfest W, et al. Coronary angioscopy in patients with unstable angina pectoris. *N Engl J Med* 1986; 315:913–919.
28. Douglas JS, Lutz JF, Clements SD, et al. Therapy of large intracoronary thrombi in candidates for percutaneous transluminal coronary angioplasty (abstr). *J Am Coll Cardiol* 1988; 11:238.
29. Vetrovec GW, Leinbach RC, Gold HR, et al. Intracoronary thrombolysis in syndromes of ischemia: Angiographic and clinical results. *Am Heart J* 1984; 104:946–952.
30. Gotoh K, Minamino T, Katoh O, et al. The role of intracoronary thrombus in unstable angina: Angiographic assessment and thrombolytic therapy during ongoing attacks. *Circulation* 1988; 77:526–534.
31. Gold HK, Johns JA, Leinbach RC, et al. A randomized, blinded, placebo-controlled trial of recombinant human tissue-type plasminogen activator in patients with unstable angina pectoris. *Circulation* 1987; 75:1192–1199.

32. Topol EJ, Nicklas JM, Kander N, et al. Need for definitive coronary revascularization despite intravenous tissue plasminogen activator (t-PA) for unstable angina: Results of a randomized, double-blind, placebo-controlled trial. *Circulation* 1987; 76(Suppl. IV):IV-452.
33. Bates ER, McGillem MJ, Mickelson JK, Pitt B, Mancini GBJ. A monoclonal antibody to the platelet receptor GPIIb/IIA (7E3) prevents acute thrombosis in a canine model of coronary angioplasty. *Circulation* 1988; 78:II-289.
34. Coller BS, Folts JD, Scudder LE, Smith SR. Antithrombotic effect of a monoclonal antibody to the platelet glycoprotein IIb/IIIa receptor in an experimental animal model. *Blood* 1986; 68:783–786.
35. Cowley MJ, Corros G, Kelsey SF, Van Raden M, Detre KM. Acute coronary events associated with percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1983; 53:12C–16C.
36. Ryan TJ, Faxon DP, Gunnar RM, et al. Guidelines for percutaneous transluminal coronary angioplasty: A report of the American College of Cardiology/American Heart Association Task Force on Assessment of Diagnostic and Therapeutic Cardiovascular Procedures (Subcommittee on Percutaneous Transluminal Coronary Angioplasty). *J Am Coll Cardiol* 1988; 12:529–545.
37. Yock PG, Linker DT. Catheter-based two-dimensional ultrasound imaging. In Topol EJ, ed, *Textbook of Interventional Cardiology*. W.B. Saunders, Philadelphia, 1990, p. 816.
38. Topol EJ, Ellis SG, Fishman J, et al. Multicenter study of percutaneous transluminal angioplasty for right coronary artery ostial stenosis. *J Am Coll Cardiol* 1987; 9:1214–1218.
39. Cote G, Myler RK, Stertzer SH, et al. Percutaneous transluminal angioplasty of stenotic coronary artery bypass grafts: 5 years' experience. *J Am Coll Cardiol* 1987; 9:8–17.
40. Douglas JS Jr., Gruentzig AR, King SB, et al. Percutaneous transluminal coronary angioplasty in patients with prior coronary bypass surgery. *J Am Coll Cardiol* 1983; 2:745–754.
41. Saber RS, Edwards WD, Holmes DR Jr., Vlietstra RE, Reeder GS. Balloon angioplasty of aortocoronary saphenous vein bypass grafts: A histopathologic study of six grafts from five patients, with emphasis on restenosis and embolic complications. *J Am Coll Cardiol* 1988; 12:1501–1509.
42. Corbelli J, Franco I, Hollman J, Simpfendorfer C, Galan K. Percutaneous transluminal coronary angioplasty after previous coronary artery bypass surgery. *Am J Cardiol* 1985; 56:398–403.
43. Kussmaul JG. Percutaneous angioplasty of coronary bypass grafts: An emerging consensus. *Cathet Cardiovasc Diag* 1988; 15:1–4.
44. Liu MW, Douglas JS, King SB, Gruentzig A. Angiographic predictors of coronary embolization in the PTCA of vein graft lesions (abstr). *Circulation* 1989; 80(Suppl. II):II-172.
45. Aueron F, Gruentzig A. Distal embolization of a coronary artery bypass graft atheroma during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1984; 53:953–954.
46. Shimshak TM, Giorgi LV, Johnson WL, et al. Application of percutaneous transluminal coronary angioplasty to the internal mammary artery graft. *J Am Coll Cardiol* 1988; 12:1205–1214.
47. Hill DM, McAuley BJ, Sheehan DJ, et al. Percutaneous transluminal angioplasty of internal mammary artery bypass grafts. *J Am Coll Cardiol* 1989; 13:221A.
48. Bell MR, Vlietstra RE, Bresnahan DR, Holmes DR. Percutaneous transluminal angioplasty of left internal mammary artery grafts using a femoral approach. *J Am Coll Cardiol* 1989; 13:221A.
49. Sketch MH, Perez JA, Quigley PJ, et al. Internal mammary artery graft angioplasty: Clinical and angiographic follow-up. *J Am Coll Cardiol* 1989; 13:221A.
50. Andreae GE, Myler RK, Clark DA, Shaw RE, Murphy MC. Acute complications following angioplasty of totally occluded vessels. *Circulation* 1987; 76(Suppl. IV):IV-400.
51. Klein LW, Agarwal JB, Helfant RH. The resolution of coronary collaterals after successful percutaneous transluminal coronary angioplasty. *Am Heart J* 1988; 115:554–558.
52. O'Keefe JH, Reeder GS, Miller GA, Bailey KR, Holmes DR. Safety and efficacy of percutaneous transluminal coronary angioplasty performed at time of diagnostic catheterization compared with that performed at other times. *Am J Cardiol* 1989; 63:27–29.
53. Schwartz L, Bourassa MG, Lesperance J, et al. Aspirin and dipyridamole in the prevention of restenosis after percutaneous transluminal coronary angioplasty. *N Engl J Med* 1988; 318:1714–1719.
54. White CW, Chaitman B, Lassar TA, et al., and the Ticlopidine Study Group (abstr). *Circulation* 1987; 76(Suppl. IV):IV-400.

55. Chesebro JH, Webster MWI, Reeder GS, Mock MB, Grill DE, Bailey KR, Steichen S, Fuster V. Coronary angioplasty: Antiplatelet therapy reduces acute complications but not restenosis (abstr). *Circulation* 1989; 80(Suppl. II):II-64.
56. Mufson L, Black A, Roubin G, et al. A randomized trial of aspirin in PTCA: Effect of high vs. low dose aspirin on major complications and restenosis (abstr). *J Am Coll Cardiol* 1988; 11:236.
57. Lembo NJ, Black AJ, Roubin GS, et al. Does the addition of dipyridamole to aspirin decrease acute coronary angioplasty complications? The results of a prospective randomized clinical trial (abstr). *J Am Coll Cardiol* 1988; 11:237.
58. Emory University Coronary Angiography Data Bank, unpublished observations.
59. Patrono C, Ciabattoni G, Patrignani P, et al. Clinical pharmacology of platelet cyclo-oxygenase inhibition. *Circulation* 1985; 72:1177–1184.
60. Paton TW, Walker SE, Leung FYK, Little AH. Effect of cimetidine on bioavailability of enteric coated aspirin tablets. *Clin Pharm* 1983; 2:165–166.
61. Swanson KT, Vlietstra RE, Holmes DR, et al. Efficacy of adjunctive dextran during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1984; 54:447–448.
62. Bygdeman S, Eliasson R, Guibring B. Effect of dextran infusion on the adenosine phosphate-induced adhesiveness and the spreading capacity of human blood platelets. *Thromb Diath Haemorrh* 1966; 15:451–456.
63. Weiss HJ. The effect of clinical dextran on platelet aggregation, adhesion, and the ADP release in man: In vivo and in vitro studies. *J Lab Clin Med* 1967; 69:37–46.
64. Data LL, Nies AS. Dextran 40. *Ann Intern Med* 1974; 81:500–504.
65. Heras M, Chesebro JH, Penny WJ, et al. Importance of adequate heparin dosage in arterial angioplasty in a porcine model. *Circulation* 1988; 78:654–660.
66. Saba HI, Saba SR, Morelli GA. Effect of heparin on platelet aggregation. *Am J Hematol* 1984; 17:295–306.
67. Salzman EW, Rosenberg RD, Smith MH, Lindon JN, Favreau L. Effect of heparin and heparin fractions on platelet aggregation. *J Clin Invest* 1980; 65:64–73.
68. Saba HI, Saba SR, Blackburn CA, Hartman RC, Mason RG. Heparin neutralization of PGI_2: Effects upon platelets. *Science* 1979; 205:499–501.
69. Ellis SG, Roubin GS, Wilentz J, Douglas JS, King SB. Effect of 18- to 24-hour heparin administration for prevention of restenosis after uncomplicated coronary angioplasty. *Am Heart J* 1989; 117:777–782.
70. Lukas MA, Deutsch E, Laskey WK. Beneficial effect of heparin therapy on PTCA outcome in unstable angina (abstr). *J Am Coll Cardiol* 1988; (Suppl. II):132.
71. Gabliani G, Deligonul U, Kern MJ, Vandormael M. Acute coronary occlusion occurring after successful percutaneous transluminal coronary angioplasty: Temporal relationship to discontinuation of anticoagulation. *Am Heart J* 1988; 116:696–700.
72. Ogilby JD, Kopelman HA, Klein LW, Agarwal JB. Adequate heparinization during PTCA: Assessment using activated clotting time (abstr). *J Am Coll Cardiol* 1988; 11:237.
73. Hariuchi K, Mizuno K, Matsui H, et al. Improved ischemic tolerance during percutaneous transluminal coronary angioplasty (PTCA) by antianginal agents (abstr). *Circulation* 1987; 76(Suppl. IV):IV-275.
74. Darius H, Schmucker B. Antianginal agents administered intracoronarily ameliorate functional impairment and extend time to ischemia during PTCA. *Circulation* 1987; 76(Suppl. IV):IV-275.
75. Lam JYT, Chesebro JH, Fuster V. Platelets. Vasoconstriction and nitroglycerin during arterial wall injury. A new antithrombotic role for an old drug. *Circulation* 1988; 78:712–716.
76. Babbit DG, Perry JM, Forman MB. Intracoronary verapamil for reversal of refractory coronary vasospasm during percutaneous transluminal coronary angioplasty. *J Am Coll Cardiol* 1988; 12:1377–1381.
77. Fischell TA, Derby G, Tse TM, Stadius ML. Coronary artery vasoconstriction routinely occurs after percutaneous transluminal coronary angioplasty. *Circulation* 1988; 78:1323–1334.
78. Hollman J, Gruentzig AR, Douglas JS Jr., King SB, Ischinger T, Meier B. Acute occlusion after percutaneous transluminal coronary angioplasty — A new approach. *Circulation* 1983; 68:725–732.
79. Sinclair IN, McCabe GH, Sipperly ME, Baim DS. Abrupt reclosure: Predictors, therapeutic options, and long-term outcome. *J Am Coll Cardiol* 1988; 11:132A.

80. Palazzo AM, Gustafson GM, Santilli E, Kemp HG. Unusually long inflation times during percutaneous transluminal coronary angioplasty. *Cathet Cardiovasc Diag* 1988; 14:154–158.
81. Smith JE, Quigley PJ, Tcheng JE, Bauman RP, Thomas J, Stack RS. Can prolonged perfusion balloon inflations salvage vessel patency after failed angioplasty? (abstr). *Circulation* 1989; 80(Suppl. II):II-373.
82. Hinohara T, Simpson JB, Phillips HR, et al. Transluminal catheter reperfusion: A new technique to reestablish blood flow after coronary occlusion during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1985; 57:684–686.
83. Hinohara T, Simpson JB, Phillips HR, Stack RS. Transluminal intracoronary reperfusion catheter: A device to maintain coronary perfusion between failed coronary angioplasty and emergency coronary bypass surgery. *J Am Coll Cardiol* 1988; 11:977–982.
84. Douglas JS, King SB, Roubin GS, Murphy DA, Namay DL, Anderson HV. Efficacy of coronary artery perfusion catheters in patients with failed angioplasty and acute myocardial ischemia. *J Am Coll Cardiol* 1987; 9:105A.
85. Sigwart U, Urban P, Golf S, et al. Emergency stenting for acute occlusion after coronary balloon angioplasty. *Circulation* 1988; 78:1121–1127.
86. Sinclair IN, Dear WE, Safian RD, Plokker TM, Spears JR, the LBA Study Group. Acute closure post PTCA successfully treated with laser balloon angioplasty (abstr). *Circulation* 1989; 80(Suppl. II):II-476.
87. Kereiakes D. Personal communication.
88. Cohen BM, Buchbinder M, Kozina J, Podolin R, Peterson KL, Ross J Jr. Rethrombosis during angioplasty in myocardial infarction and unstable syndromes: Efficacy of intracoronary urokinase and redilation (abstr). *Circulation* 1988; 78(Suppl. II):II-8.
89. Curling PE, Weintraub WS, Jones EL, Talley D, Craver JM, Guyton RA. Failed elective coronary angioplasty mandating bypass surgery vs. elective coronary surgery: A case control study. *Circulation* 1988; 78(Suppl. II):II-476.
90. Ellis SG, Roubin GS, King SB, et al. In-hospital cardiac mortality after acute closure after coronary angioplasty: Analysis of risk factors from 8207 procedures. *J Am Coll Cardiol* 1988; 11:211–216.
91. Park DD, Laramee LA, Teirstein P, et al. Major complications during PTCA: An analysis of 5413 cases (abstr). *J Am Coll Cardiol* 1988; 11:237.
92. Harnarayan C, Bennett, MA, Pentecost BL, Brewer DB. Quantitative study of infarcted myocardium in cardiogenic shock. *Br Heart J* 1970; 32:728–732.
93. Kalbfleisch H, Hort W. Quantitative study on the size of coronary artery supplying areas postmortem. *Am Heart J* 1977; 94:183–188.
94. James TN. Anatomy of the coronary arteries in health and disease. *Circulation* 1965; 32:1020–1029.
95. Kennedy JW, Kaiser G, Fisher L. Multivariate discriminant analysis of the clinical and angiographic predictors of operative mortality from the collaborative study in coronary artery surgery (CASS). *J Thorac Cardiovasc Surg* 1980; 80:876–882.
96. Kennedy JW, Kaiser G, Fisher L, et al. Clinical and angiographic predictors of operative mortality from the collaborative study in coronary artery surgery (CASS). *Circulation* 1981; 63:793–799.
97. Kirklin JW, Blackston E, Rogers WJ. The plights of the invasive treatment of ischemic heart disease. *J Am Coll Cardiol* 1985; 5:158–167.
98. Vogel RA. Supported angioplasty. In Topol EJ, ed, *Textbook of Interventional Cardiology*. W.B. Saunders, Philadelphia, 1990, pp. 467–476.
99. Smalling RW, Sweeney MJ, Cassidy DB, Barrett RL, Morris RE, Lammermeier DE, Key PG, Haynie MP, Frazier OH, Wampler R. Hemodynamics in cardiogenic shock after acute myocardial infarction with the hemopump assist device. *Circulation* 1989; 80(Suppl. II): II-624.
100. Jacobs AK, Faxon DP. Retroperfusion and PTCA. In Topol EJ, ed, *Textbook of Interventional Cardiology*. W.B. Saunders, Philadelphia, 1990, pp. 477–495.

2. MYOCARDIAL PROTECTION DURING CORONARY ANGIOPLASTY

DANIEL WOHLGELERNTER

Since Dr. Andreas Gruentzig's initial description in 1977 of this innovative therapeutic technique, percutaneous transluminal coronary angioplasty (PTCA) has revolutionized the practice of cardiology [1]. Originally envisioned by its creator as a less traumatic alternative to coronary bypass surgery for a select subset of patients with single-vessel disease, PTCA is now considered a mainstream therapy for angina with multivessel disease, unstable angina, acute myocardial infarction, and post-bypass surgery angina [2].

One of the most instructive aspects of the proliferation of angioplasty applications is the insight that has been provided into the physiologic consequences of coronary artery occlusion in conscious human subjects. Prior to the advent of PTCA, the evaluation of ischemia-induced regional myocardial dysfunction in humans had been limited to diagnostic observations during acute coronary vasospasm, acute myocardial infarction, and open-heart surgery. Coronary angioplasty provides an opportunity to assess alterations in function of the myocardium in a zone of transient ischemia. Inflating the angioplasty balloon causes total coronary occlusion, recreating the conditions found in experimental models of transient myocardial ischemia.

The mechanical myocardial consequences of coronary occlusion during PTCA are similar to those described in experimental occlusion studies in animals, with echocardiographic studies demonstrating the development of hypokinesis of the region subserved by the dilated artery within 15–20 seconds, progressing to akinesis or dyskinesis within 45–50 seconds of balloon

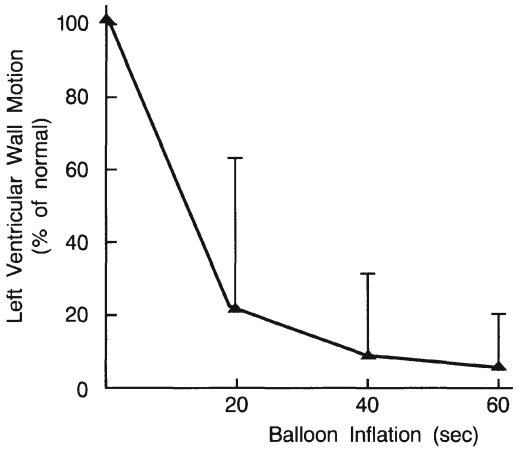

Figure 2-1. Effect of balloon occlusion on regional LV function. Adapted from Wohlgelernter et al. *J Am Coll Cardiol* 1986; 7:1245–1254. With permission.

inflation [3–6]. Figure 2-1 illustrates the time course of regional left ventricular dysfunction during balloon inflation. In patients with normal baseline left ventricular systolic function, the regional dysfunction induced by balloon inflation is generally reversible and well tolerated, and there appears to be no cumulative effect of multiple inflations [3]. However, there are doubts regarding the applicability of these findings to patients with preexisting significant ventricular dysfunction. Accordingly, PTCA investigators have moved to address the troublesome problem of intraprocedural ischemia.

In this chapter, the characteristics of the ischemic manifestations of balloon occlusion will be reviewed, and the methods, objectives, and results of various approaches to protect the ischemic myocardium during PTCA will be discussed.

ISCHEMIC CONSEQUENCES OF ANGIOPLASTY

There is a predictable pattern of ischemic manifestations of coronary occlusion that evolves during the course of a single balloon inflation. Figure 2-2 depicts the temporal sequence of events during balloon occlusion. During the first few seconds in severely ischemic tissue with little or no collateral flow, available oxygen is expended and anaerobic conditions develop within the cells. This state of oxygen deprivation invokes sensitive cellular control mechanisms that trigger major changes in substrate uptake and utilization patterns [7]. These biochemical and metabolic manifestations of ischemia have been documented during PTCA [8], but they can not be feasibly evaluated by the clinician.

Profound disruption of diastolic function has been demonstrated as an

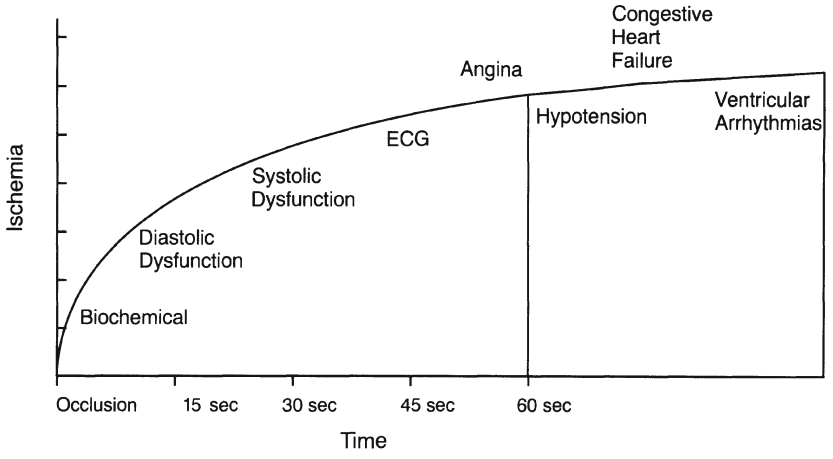

Figure 2-2. Sequence of events during balloon occlusion. Adapted from Kern M, et al. *Am Heart J* 1989; 118:361. With permission.

inevitable consequence of balloon occlusion. Serruys reported that some relaxation parameters deteriorated within 17 seconds of occlusion, while other parameters — including left ventricular end-diastolic pressure — decayed more gradually [8]. Doppler echocardiographic assessment revealed a 35% decrease in the early peak filling rate during PTCA of the left anterior descending (LAD) coronary artery [9]. Though all of the above-mentioned studies indicated that ventricular function returns to baseline levels within 2 minutes after balloon deflation, Wijns et al. reported that regional diastolic stiffness persisted 12 minutes after the completion of the PTCA procedure [10].

Systolic ventricular dysfunction has been well described during balloon inflation, as previously noted. Detailed analysis of baseline and intraprocedural left ventricular contrast angiograms demonstrated the onset of marked systolic dysfunction beginning about 20 seconds after balloon inflation [8]. In the context of angioplasty of a proximal LAD stenosis, this regional dysfunction can account for a substantial impairment in global ejection fraction, as demonstrated in Figure 2-3.

These massive abnormalities in diastolic and systolic ventricular performance are often reflected in major changes in measured hemodynamic variables. In a series of 10 patients undergoing PTCA of proximal LAD lesions, pulmonary wedge pressure rose from a baseline of 10 ± 2 mmHg to 25 ± 4 mmHg after 60 seconds of occlusion [11].

Ischemic ECG changes lag behind the onset of wall motion abnormalities, with only 64% of patients showing evidence of ischemia on 12-lead tracings at 20 seconds of inflation. After 60 seconds, 86% had ischemia detectable by

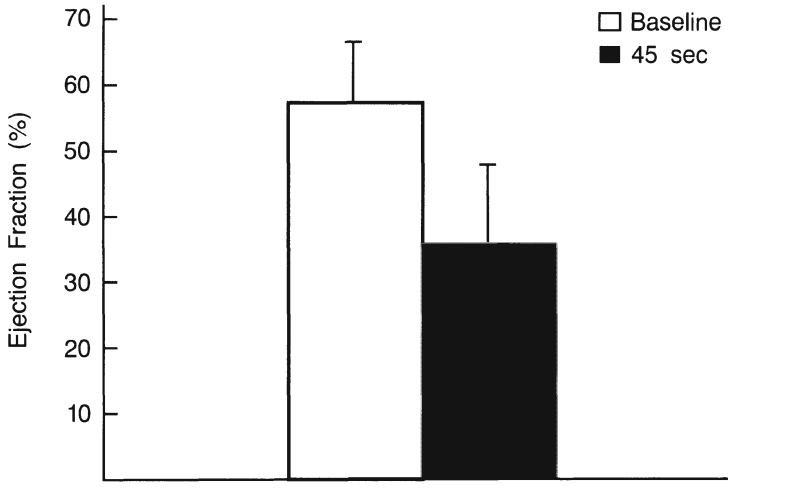

Figure 2-3. Ejection fraction during angioplasty. Adapted from Jaffe C, et al. *Am Heart J* 1988; 115:1156–1164. With permission.

ECG [3]. Monitoring limited to the standard limb leads results in a substantial reduction in the ability of the ECG to detect ischemia during inflation.

Angina is an expected consequence of balloon inflation and tends to be closely monitored in the clinical setting. However, the onset of anginal pain usually is substantially later than the onset of functional and ECG changes. Indeed, significant myocardial ischemia, manifested by profound global and regional myocardial dysfunction and ST-segment deviations, has been reported in the absence of any pain [12]. While the appearance of angina has been a commonly used endpoint for balloon inflation, it is now apparent that the absence of pain does not reflect the absence of severe left ventricular dysfunction.

The clinical effects of ischemia during PTCA can be categorized as follows: a) *mechanical "pump" dysfunction* of the ischemic ventricular segment, b) *electrical abnormalities*, and c) *anginal pain*. The impact that these ischemic consequences exert on an individual angioplasty procedure depends, to a large extent, on the baseline physiology of the patient undergoing the procedure and the strategic importance of the artery to be dilated. Thus, a patient with preexisting major ventricular dysfunction will be more vulnerable to the additional mechanical dysfunction induced by balloon inflation, and there may ensue frank acute pump failure, with hypotension and systemic hypoperfusion. Similarly, the patient with an enormous ischemic burden during the dilatation sequence may develop serious ventricular arrhythmias or conduction disturbances (Figure 2-4). In a practical sense, mitigation of ischemia is an

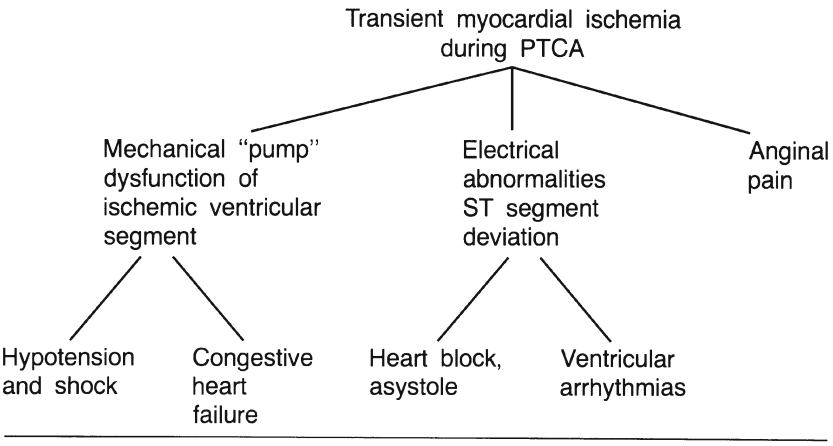

Figure 2-4. Clinical effects of ischemia during PTCA.

important objective in the strategic approach to such "high risk" patients, not only to avoid ischemic complications, but also to prevent premature termination of procedures or suboptimal inflation durations, which may limit the short- and long-term success rates of PTCA.

IDENTIFICATION OF THE "HIGH RISK" PATIENT

As documented in the NHLBI Registry data from 1985–86, the typical angioplasty patient has changed considerably since the early days of PTCA. Today, 25% of patients present with compromised ventricular function, as evidenced by depressed ejection fractions or histories of congestive heart failure [13]. Despite the expansion of the pool of eligible patients to include those with more compromised myocardium and more complex coronary lesions, angioplasty has been increasingly successful [13]. Nevertheless, there remains a significant group of patients for whom PTCA is deemed prohibitively risky because of potential ischemic consequences. Preprocedural identification of such "high risk" patients is needed to allow appropriate targeting of myocardial protection measures.

Dr. Vlietstra and colleagues at the Mayo Clinic have provided a classification system of multivessel coronary patients that is useful for identifying the "high risk" patient (Figure 2-5). Clearly, patients with Type C or Type D anatomy will be at higher risk for intraprocedural ischemic consequences in view of their total ischemic burden during balloon occlusion. Analysis of other clinical variables, such as baseline ejection fraction, nature of collateral protection, and complexity of target lesions, provides additional levels of refinement in defining risk status.

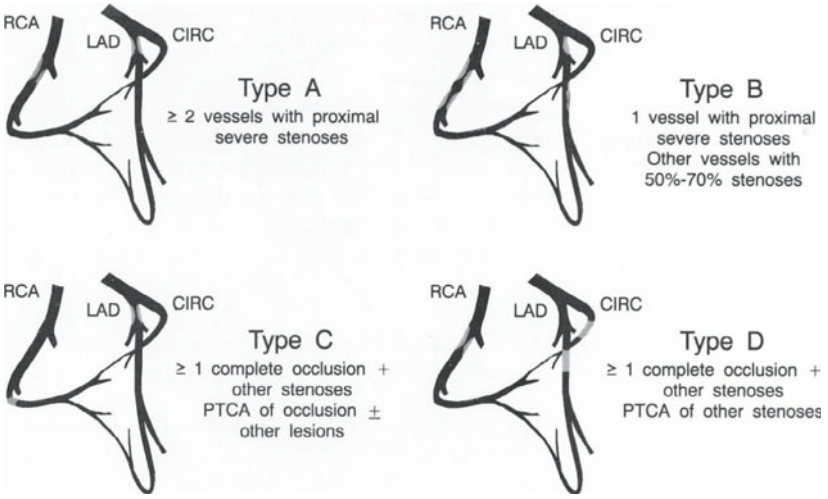

Figure 2-5. Types of multivessel coronary artery disease. Adapted from Vlietstra R. In *PTCA: Percutaneous Transluminal Coronary Angioplasty*. F.A. Davis, Philadelphia, 1986. With permission.

MYOCARDIAL PROTECTION VERSUS CARDIAC SUPPORT

Interventions to counteract the effects of ischemia during PTCA can be assigned to two broad categories: a) *myocardial protection* — mitigation of ischemia produced by balloon occlusion by favorably affecting the myocardial oxygen supply/demand balance; and b) *cardiac support* — augmentation of systemic perfusion during periods of myocardial ischemia by the use of mechanical assist devices.

Efforts at achieving myocardial protection during PTCA have focused on four basic approaches: a) pharmacologic adjuncts to decrease myocardial oxygen demand or augment collateral flow; b) distal coronary artery perfusion, either with arterial blood or with an oxygen-transporting perfluorochemical emulsion delivered through the central lumen of the dilating catheter; c) autoperfusion of the distal vessel by the use of specially designed continuous perfusion balloon catheters; and d) synchronized coronary sinus retroperfusion, i.e., retrogradely perfusing the jeopardized region via the coronary venous system.

PHARMACOLOGIC INTERVENTIONS

Pharmacologic measures to attenuate the ischemic response include the use of systemically administered agents, as well as regional protective interventions in which agents are administered directly into the coronary circulation. Intra-

venous nitroglycerin, given before balloon inflation, can delay the onset of ischemic ECG changes and angina symptoms [14]. A variable response has been reported with intravenous propranolol (0.1 mg/kg) given during PTCA of LAD stenoses, with a beneficial effect on ischemia demonstrated in 10 of 16 patients, but no mitigation of ischemia in the remaining six patients, despite a similar reduction in heart rate [15]. A more consistent level of benefit has been seen with the administration of propranolol into the coronary artery through the dilatation catheter positioned across the stenosis. The time to onset of ST elevation was increased from 19 to 53 seconds and the magnitude of ST deviation was reduced from 0.23 to 0.12 mV after the injection of 0.5–2.0 mg of intracoronary propranolol [16]. The protective effect occurred despite the absence of changes in heart rate or arterial pressure, suggesting that regional beta blockade resulted in a reduction of local myocardial oxygen consumption in the jeopardized zone secondary to a regional reduction in contractility.

Calcium-channel blockers have been applied both intravenously and by the intracoronary route during PTCA procedures. Nicardipine, given intravenously to patients undergoing LAD angioplasty, diminished ischemia by increasing collateral flow and by decreasing oxygen demand [17]. Intracoronary nicardipine, administered before balloon inflation, reduced ischemia by a presumed direct protective effect on myocardial cells [18]. Similarly, intracoronary diltiazem [19] and intracoronary nifedipine [20] affected ischemia reduction due to regional cardioplegic effects. Intravenous diltiazem and sublingual nifedipine have both been shown to have similar effects on prolonging the time to ischemic ST segment deviation via their beneficial impact on myocardial oxygen demand [21].

DISTAL CORONARY PERFUSION STRATEGIES

Though pharmacologic measures to prevent ischemia during PTCA are associated with a credible measure of efficacy, the cardioprotection these agents confer is probably inadequate for patients with precarious left ventricular function. Consequently, attempts have been made to provide oxygen to the myocardium during balloon inflation by intraprocedural perfusion of blood into the distal coronary artery. Studies evaluating the effects of distal perfusion with arterial blood [22] and renal vein blood [23] demonstrated a marked reduction in all indicators of ischemia.

Though these data suggest that blood perfusion into the distal artery may be a feasible approach for myocardial protection, there are lingering concerns about the logistics of this method of intervention. The viscosity of whole blood makes its delivery via the distal lumen of the angioplasty catheter quite difficult, and its infusion at high flow rates may result in significant hemolysis.

Another approach is represented by distal coronary perfusion with oxygenated fluorocarbons delivered at the time of balloon occlusion.

The perfluorochemicals are chemically inert compounds that have an exten-

sive capacity for dissolving, transporting, and releasing oxygen. In the 1970s, the Green Cross Corporation of Japan developed an emulsified formulation of two perfluorochemicals: perfluorodecalin and perfluorotri-*n*-propylamine. This formulation, Fluosol® (20% intravascular perfluorochemical emulsion), has been shown to be effective in delivering oxygen to ischemic myocardial tissue during PTCA [24–26]. The Fluosol perfusate is oxygenated, in vitro, to a PO_2 of greater than 600 mmHg by using a mixture of 95% oxygen and 5% carbon dioxide bubbled through the solution for 15–30 minutes. The solution is warmed to 37°C in a water bath before administration. During balloon inflation, oxygenated Fluosol is perfused through the central lumen of the balloon catheter, with the guidewire in place in the distal vessel at flow rates of 45–60 ml/min. Cleman and colleagues reported a >90% preservation of regional chord shortening, as judged by quantitative echocardiographic analysis, during PTCA balloon inflations with Fluosol distal perfusion, as compared with only 6% residual function without distal perfusion at 60 seconds after balloon inflation [24]. Cowley et al. evaluated the efficacy of distal coronary perfusion with Fluosol during PTCA in patients with unstable ischemic syndromes and in patients with impaired left ventricular function [26]. Fluosol perfusion was associated with significant reduction of balloon-induced myocardial ischemia, determined by preservation of cardiac output and of global and regional left ventricular function during balloon occlusion.

Intracoronary perfusion with oxygenated Fluosol has proven to be remarkably well tolerated. In clinical trials, immediate adverse reactions occurred only rarely and were either self-limiting or readily controlled. The perfluorochemical particles of Fluosol are better suited than whole blood for oxygen transport in the face of ischemic challenge. They are approximately 1/9000 the volume of erythrocytes. In addition, the viscosity of Fluosol is only 50% that of whole blood. Consequently, Fluosol can be perfused through a narrow lumen and is able to penetrate coronary microvascular beds that are typically inaccessible to red blood cells.

AUTOPERFUSION

Another approach to myocardial protection during balloon inflation involves the application of passive autoperfusion of the distal vessel. Using a specially designed balloon catheter, the arterial blood enters the central lumen of the catheter via the proximal side holes and exits through the distal side holes (i.e., distal to the balloon) into the coronary bed. During a 3-minute balloon occlusion, autoperfusion prevented ST-segment elevation [27]. Quigley et al. found that autoperfusion allowed significant prolongation of inflation time from 107 ± 55 seconds to 513 ± 303 seconds in 11 patients undergoing PTCA [28]. Prolonged (15-minute) autoperfusion balloon angioplasty has been evaluated and has been demonstrated to be efficacious, without clinical evidence of myocardial damage or hemolyis [29].

SYNCHRONIZED RETROPERFUSION

Though distal perfusion techniques are an important adjunct to PTCA, allowing longer inflation times and enhancing the safety of PTCA in "high risk" situations, they are limited by certain logistical constraints. Distal perfusion with blood or Fluosol mandates use of double-lumen balloon catheters. Several newer dilatation catheters dispensed with the double-lumen architecture to minimize the diameter of the catheter shaft. Moreover, distal perfusion techniques cannot provide protection to major side branches that are occluded by the inflated balloon segment. Similarly, autoperfusion balloon angioplasty is limited by the side-branch issue, and the inherent technical difficulties of using the less flexible, wider caliber autoperfusion catheter.

An alternative means of protecting the myocardium during PTCA is retroperfusion via the coronary sinus. An old idea, retrograde perfusion and arterialization of coronary veins, was conceptualized by Pratt in 1898 and applied by Beck in the early 1940s before the introduction of coronary artery revascularization surgery. With synchronized retroperfusion, developed in the early 1970s by Meerbaum and colleagues [30], blood from a suitable arterial site is pumped during diastole into the coronary sinus and then subselectively into the regional coronary veins draining the jeopardized myocardium. This allows venous drainage during systole and minimized vascular congestion and myocardial edema.

Berland et al. have reported on their experience with retroperfusion application in 16 patients undergoing PTCA of proximal LAD stenosis [31]. Arterial blood retroperfusate was delivered through an 8 Fr multiple end-hole catheter placed percutaneously within the left femoral artery. The pumped retroperfusate flowed into the coronary sinus via an 8 Fr autoinflatable balloon catheter that was passed through a 9 Fr sheath inserted through the right internal jugular vein. This balloon catheter was positioned in the coronary sinus, with the tip of the catheter placed, if possible, in the great cardiac vein. A single retroperfusion-treated LAD occlusion was compared with equivalent untreated control LAD occlusions. Treated occlusions exhibited delayed or significantly lower ST-segment elevations as compared with controls. Two-dimensional echocardiographic observations in controls showed significantly more severe global left ventricular dysfunction, whereas retroperfusion support tended to maintain global function and ameliorated regional contraction abnormalities. The study also illustrated some of the technical difficulties and limitations of this technique, including nonoptimal catheter placement in the coronary veins, insufficient retroperfusate flow rate, and inadequate diastolic pressure augmentation.

The retroperfusion approach has the following attractive procedural characteristics: a) minimal inteference with the primary PTCA procedure; b) application does not require the use of specific balloon angioplasty catheters; c) theoretically, large side branches should be equally protected via the venous retroperfusion; and d) it can be utilized as a "bridge" to support and protect

the jeopardized myocardium during abrupt closure of the dilated coronary vessel, pending restoration of arterial flow, either via repeat dilatation, passage of a perfusion "bailout" catheter, or surgical revascularization.

SUPPORTED ANGIOPLASTY

While the myocardial protection measures discussed above are primarily intended to mitigate the ischemia that inevitably develops during balloon inflation, cardiac support techniques are designed to circumvent the potential problems of hemodynamic collapse following abrupt closure of the dilated coronary artery in high-risk patients. Though these support techniques may also primarily ameliorate myocardial ischemia, their major benefits derive from support of the systemic circulation.

The approaches to supporting the systemic circulation during high-risk angioplasty procedures include utilization of the following devices: a) intraaortic balloon pump, b) percutaneous cardiopulmonary bypass system, and c) intraventricular pumping (Hemopump).

INTRAAORTIC BALLOON COUNTERPULSATION

Intraaortic balloon pumping (IABP) has been used as a prophylactic intervention in high risk angioplasty patients. Voudris and colleagues reported on their experience with 24 patients with poor left ventricular function (ejection fraction <40%) undergoing PTCA of arteries contralateral to totally occluded infarction-related vessels [32]. With prophylactic use of IABP, all the procedures were successfully performed, without major complications. However, IABP only augments cardiac output 20–30% and is of no value in the presence of arrhythmias, such as ventricular tachycardia or fibrillation.

PERCUTANEOUS CARDIOPULMONARY SUPPORT

This exciting and elaborate approach to cardiac support is extensively reviewed elsewhere in this text. This technique utilizes a cardiopulmonary bypass system, which includes a Biomedicus centrifugal pump placed proximal to a membrane oxygenator. Blood is actively aspirated from the right atrium and inferior vena cava, using 18–20 Fr cannulae, and then directed into the heat exchanger, after which it is pumped through the membrane oxygenator and then, by percutaneously placed arterial cannula, to the distal aorta. In contrast to the IABP method, this system provides systemic perfusion of up to 5 l/min, independent of cardiac rate and cardiac output. Though this cardiopulmonary bypass system provides full circulatory support, it does not prevent regional myocardial ischemia, because direct myocardial perfusion is not provided.

LEFT VENTRICULAR BYPASS SUPPORT

Two types of left ventricular bypass support are being evaluated for supported angioplasty. The first uses transseptal cannulation of the left atrium in conjunction with synchronized pumping into the femoral artery [33]. An

alternative left ventricular support system uses an axial flow pump placed transfemorally across the aortic valve. This device, called the Hemopump, is capable of pumping 3–4 l/min, and provides support of systemic perfusion, as well as unloading of the left ventricle [34].

INDICATIONS FOR USE OF PROTECTION AND SUPPORT MEASURES

Myocardial protection methods and systemic circulatory support devices are not mutually exclusive. Combination therapy employing distal perfusion with blood or Fluosol for ischemia mitigation in conjunction with standby percutaneous cardiopulmonary support certainly has an appealing rationale for the high risk patient (e.g., Mayo Clinic Type D anatomy) undergoing PTCA. On the other hand, one must weigh the merits of these measures against their cost and potential associated morbidity. As with other decisions in today's climate of "high-tech" interventions, application of these tools must be based on a careful, premeditated risk-benefit analysis.

REFERENCES

1. Gruntzig AR, Senning A, Siegenthaler WF. Nonoperative dilatation of coronary artery stenosis: Percutaneous transluminal coronary angioplasty. *N Engl J Med* 1979; 301:61–68.
2. Holmes DR, Vlietstra RE, Percutaneous transluminal coronary angioplasty: Current status and future trends. *Mayo Clin Proc* 1986; 61:865–876.
3. Wohlgelernter D, Cleman M, Highman HA, Fetterman RC, Duncan JS, Zaret BL, Jaffe CC. Regional myocardial dysfunction during coronary angioplasty: Evaluation by two-dimensional echocardiography and 12 lead electrocardiography. *J Am Coll Cardiol* 1986; 7:1245–1254.
4. Hauser AM, Gangadharan V, Ramos RG, Gordon S, Timmis GC. Sequence of mechanical, electrocardiographic and clinical effects of repeated coronary artery occlusion in human beings: Echocardiographic observations during coronary angioplasty. *J Am Coll Cardiol* 1985; 5:193–197.
5. Visser CA, David GK, Kan G, Romijn KH, Meltzer RS, Koolen JJ, Dunning AJ. Two-dimensional echocardiography during percutaneous transluminal coronary angioplasty. *Am Heart J* 1986; 111:1035–1041.
6. Alam M, Khaja F, Brymer J, Marzelli M, Goldstein S. Echocardiographic evaluation of left ventricular function during coronary artery angioplasty. *Am J Cardiol* 1986; 57:20–25.
7. Opie LH. Metabolism of the heart in health and disease. Part I. *Am Heart J* 1968; 76:685–698.
8. Serruys PW, Wijns W, van den Brand M, Meij S, Slager C, Schuurbiers JCH, Hugenholtz PG, Brower RW. Left ventricular performance, regional blood flow, wall motion, and lactate metabolism during transluminal angioplasty. *Circulation* 1984; 70:25–36.
9. Bowman LK, Cleman MW, Cabin HS, Zaret BL, Jaffe CC. Dynamics of early and late left ventricular filling determined by Doppler two-dimensional echocardiography during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1988; 61:541–545.
10. Wijns W, Serruys PW, Slager CJ, Orimm J, Krayenbuehl HP, Hugenholtz PG, Hess OM. Effect of coronary occlusion during percutaneous transluminal angioplasty in humans on left ventricular chamber stiffness and regional diastolic pressure-radius relations. *J Am Coll Cardiol* 1986; 455–463.
11. Simon R, Amede I, Lichtlen PR. Coronary blood flow and hemodynamics during prolonged balloon inflation in coronary angioplasty. *J Am Coll Cardiol* 1984; 3:507A.
12. Wohlgelernter D, Jaffe CC, Cabin HS, Yeatman LA, Cleman M. Silent ischemia during coronary occlusion produced by balloon inflation: Relation to regional myocardial dysfunction. *J Am Coll Cardiol* 1987; 10:491–498.
13. The National Heart, Lung and Blood Institute Registry. Percutaneous transluminal coronary angioplasty in 1985–1986 and 1977–1981. *N Engl J Med* 1988; 318:265–270.
14. Doorey AJ, Mehmel HC, Schwarz FX, Kubler W. Amelioration by nitroglycerin of left ventricular ischemia induced by percutaneous transluminal coronary angioplasty: Assessment

by hemodynamic variables and left ventriculography. *J Am Coll Cardiol* 1985; 6:267–274.
15. Feldman RL, MacDonald RG, Hill JA, Limacher MC, Conti CR, Pepine CJ. Effect of propranolol on myocardial ischemia occurring during acute coronary occlusion. *Circulation* 1986; 73:727–733.
16. Zalewski A, Goldberg S, Dervan JP, Slysh S, Maroko PR. Myocardial protection during transient coronary artery occlusion in man: Beneficial effects of regional beta-adrenergic blockade. *Circulation* 1986; 73:734–739.
17. Feldman RL, MacDonald RG, Hill JA, Pepine CJ. Effect of nicardipine on determinants of myocardial ischemia occurring during acute coronary occlusion produced by percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1987; 60:267–270.
18. Hanet C, Rousseau MF, Vincent MF, Lavenne-Pardonge E, Pouleur H. Myocardial protection by intracoronary nicardipine administration during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1987; 1035–1040.
19. Kober G, Kastner R, Hopf R, Kaltenbach M. Die direkte myokardiale antiischamische wirkung von diltiazem beim menschen. *Z Kardiol* 1986; 75:386–393.
20. Pop G, Serruys PW, Piscione F, de Feyter P, van den Brand M, Huizer T, de Jong JW, Hugenholtz PG. Regional cardioprotection by subselective intracoronary nifedipine is not due to enhanced collateral flow during coronary angioplasty. *Int J Cardiol* 1987; 16:27–41.
21. Kern MJ, Deligonul U, Labovitz A. Effects of diltiazem and nifedipine on systemic and coronary hemodynamics and ischemic responses during transient coronary artery occlusion in patients. *Am Heart J* 1990; 119:47–54.
22. Timmis AD, Crick JCP, Griffin B. Arterial blood infusion for myocardial protection during PTCA. *J Am Coll Cardiol* 1986; 7:105A.
23. Angelini P, Heibig J, Leachman R. Distal hemoperfusion during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1986; 58:252–255.
24. Cleman M, Jaffe CC, Wohlgelernter D. Prevention of ischemia during percutaneous transluminal coronary angioplasty by transcatheter infusion of oxygenated Fluosol DA 20%. *Circulation* 1986; 74:555–562.
25. Jaffe CC, Wohlgelernter D, Cabin H, Bowman L, Deckelbaum L, Remetz M, Cleman M. Preservation of left ventricular ejection fraction during percutaneous transluminal coronary angioplasty by distal transcatheter coronary perfusion of oxygenated Fluosol DA 20%. *Am Heart J* 1988; 115:1156–1164.
26. Cowley MJ, Snow FR, DiSciascio G, Kelly K, Guard C, Nixon JV. Perfluorochemical perfusion during coronary angioplasty in unstable and high-risk patients. *Circulation* 1990; 81(Suppl. IV):27–34.
27. Turi ZG, Campbell CA, Gottimukkala MV, Kloner RA. Preservation of distal coronary perfusion during prolonged balloon inflation with an autoperfusion angioplasty catheter. *Circulation* 1987; 75:1273–1280.
28. Quigley PJ, Hinohara T, Phillips HR, Peter RH, Behar VS, Kong Y, Simonton CA, Perez JA, Stack RS. Myocardial protection during coronary angioplasty with an autoperfusion balloon catheter in humans. *Circulation* 1988; 78:1128–1134.
29. Muhlestein JB, Quigley PJ, Phillips HR, Smith JE, Enos SM, Navetta FI, Tcheng JE, Stack RS. Does myocardial damage or hemolysis occur during prolonged perfusion balloon angioplasty? *J Am Coll Cardiol* 1990; 15:250A.
30. Meerbaum S, Lang TW, Osher JV, Hashimoto K, Lewis GW, Feldstein C, Corday E. Diastolic retroperfusion of acutely ischemic myocardium. *Am J Cardiol* 1976; 37:588–597.
31. Berland J, Farcot JC, Barrier A, Dellac A, Gamra H, Letac B. Coronary venous synchronized retroperfusion during percutaneous transluminal angioplasty of left anterior descending coronary artery. *Circulation* 1990; 81(Suppl. IV):35–42.
32. Voudris V, Marco J, Morice MC, Fajadet J, Royer T. "High-risk" percutaneous transluminal coronary angioplasty with preventive intra-aortic balloon counterpulsation. *Cathet Cardiovasc Diag* 1990; 19:160–164.
33. Shani J, Hollander G, Nathan I, Greengart A, Toporoff B, Jacobowitz I, Glassman E, Cunningham J, Lichstein E. Percutaneous left atrial-femoral artery bypass with a pulsatile pump: Initial experience in cardiogenic shock. *J Am Coll Cardiol* 1989; 13:53A.
34. Loisance D, Dubois-Rande JL, Deleuze P, Okude J, Rosenval O, Geschwind H. Prophylactic intraventricular pumping in high-risk coronary angioplasty. *Lancet* 1980; 335:438–440.

SECTION II

3. EXTRACORPOREAL CARDIOPULMONARY BYPASS SUPPORT: A HISTORICAL AND CURRENT PERSPECTIVE

A. KENNETH LITZIE

INTRODUCTION

In 1985, a system composed of a small, portable cart-mounted blood pump, a preassembled perfusion circuit, and percutaneous femoral access cannulae was introduced for the treatment of patients with life-threatening cardiac and/or pulmonary dysfunction. The system could be used anywhere in the hospital as a fast, effective means of circulatory and respiratory support.

The current level of interest in using femoro-femoral cardiopulmonary bypass support (CPS) in areas other than the cardiac surgical suite is an evolutionary extension of encouraging, though suboptimal, clinical experience accrued since 1957. Contributing to the present scope of CPS applications is a better understanding of indications and a marked improvement in cardiopulmonary support technology.

This chapter will describe utilization of cardiopulmonary bypass in noncardiac surgical settings. The discussion will cover both historical and current trends in medical thought and the use of available technology.

Historical perspective

In 1953 [1], Gibbon introduced mechanical cardiopulmonary bypass support. His device was intended primarily as a mechanism to facilitate surgical repair of congenital and acquired cardiac defects. Four years later, Stuckey and Newman [2–3] successfully applied what was then known as a pump-oxygenator circuit to palliate the life-threatening symptoms of cardiogenic

shock. His patients were placed on cardiopulmonary bypass after 12–52 hours of intractable shock secondary to myocardial infarction. Once on bypass, there was no definitive therapy available, but it was sometimes possible for the patient to be weaned from maximal pharmacologic therapy.

In 1961, Cooley and Beall [4] published the first report of a successful pulmonary embolectomy procedure conducted while the patient was supported with standard cardiopulmonary bypass in the operating room. Deterioration of vital signs after 36 hours of maximal medical management was the indication to support this patient with cardiopulmonary bypass. This case demonstrated that CPS was a useful adjunctive therapy for temporary support of cardiac or pulmonary function. When compared to the cardiogenic shock patient population reported on by Stuckey (for whom no definitive therapy was available for pathologies such as coronary artery disease), the use of short-term circulatory and/or respiratory support proved extremely effective as a life-sustaining mechanism during crises attributable to potentially reversible pathologies.

Mattox and Beall [5–7] coroborated the effectiveness of temporary circulatory support with CPS in a series of 43 moribund patients. Prompt initiation of CPS in this group resulted in a 40% long-term survival rate (17 patients up to 10 years). Patients with pulmonary embolus, cardiopulmonary trauma, massive drug overdose, and cardiogenic shock were successfully supported on femoro-femoral cardiopulmonary bypass. Documenting such a notable success rate in patients "who would unquestionably have died without resuscitative cardiorespiratory support and subsequent surgery", the authors underscored what was then, and perhaps still is, the unrealized potential value of femoro-femoral cardiopulmonary bypass support in the clinical armamentarium.

Other investigators [8–11] documented the value of both standard and femoro-femoral cardiopulmonary bypass as a form of circulatory support for patients *in extremis*. In 1969, Kennedy [12] compiled and reviewed the outcome of 198 patients who had received "assisted circulation" of various types. Of his last 26 patients, 81% [21] were supported with CPS, and of those 21 patients, 43% were salvaged and discharged.

Kennedy included in his review the first published outline of what he thought, based on his own experience and analysis of the literature, to be prudent indications and contraindications for CPS. Falling into three general categories, Kennedy's indications are outlined in Table 3-1.

These recommendations, with few qualifications, are as applicable today as they were over 20 years ago when they were first published.

Between 1970 and 1971, other well-known groups began to publish retrospective analyses of patients supported on cardiopulmonary bypass that had occurred as early as 1960. Though dated even then, Lande and Edwards [13], Kennedy and Bricker [14], May and Hardy [15], LeFemine and Harken [16], and Baird and de la Rocha [17] each acknowledged that the use of CPS sup-

Table 3-1. Indications for cardiac support — 1969

1. Cardiac arrest refractory to resuscitation
   a. With "live" brain
   b. With "live" heart
   c. Without other incurable disease
2. Cardiac failure refractory to treatment
3. In situ short-term organ preservation

Table 3-2. Elective FF-CPB indications — 1973

1. Preoperative circulatory support in the presence of florid heart failure or shock
2. Preoperative circulatory support for reoperations, or cardiac or aortic arch aneurysms
3. Elective intracardiac procedures through a left thoracotomy
4. Partial cardiopulmonary bypass for operations on the descending thoracic aorta

port demonstrated potential value in temporizing the critical presentations of pathologies as diverse as cardiogenic shock, unresuscitable cardiac arrest, postcardiotomy low cardiac output failure, acute and chronic pulmonary insufficiency, rheumatic heart disease, myocardial infarction, dissecting aortic aneurysm, status asthmaticus, pulmonary embolus, ruptured chorda tendinea, anesthetic accident, traumatic rupture of the aorta, aortopulmonary fistula, and penetrating thoracic trauma. Results were predictably variable, but overall displayed an encouraging temporal trend toward rational decision making in what were most often emergency circumstances.

The next set of published indications for femoro-femoral cardiopulmonary bypass reflected a new awareness surrounding prudent use of this still relatively new life-support technology. Berger et al. [18] in 1973 reported on 117 patients for whom CPS was not used as a definitive therapy (e.g., for an MI patient before coronary revascularization was available), rather, it was used only as a temporary life-support mechanism immediately before or during a therapeutic procedure directed at the patient's underlying pathology. The four indications (Table 3-2) under which all 117 were electively selected set somewhat of a precedent as being largely prophylactic in nature.

It was becoming clear that the technique of CPS was effective enough to continue to broaden the indications for its use. Town and associates [19] built on previous work [20–22] to successfully utilize CPS to reverse intractable ventricular fibrillation associated with profound accidental hypothermia. These papers formed a foundation upon which many others would apply cardiopulmonary bypass to treat profound hypothermia.

Through the 1970s and into the early 1980s [23–28], femoro-femoral cardiopulmonary bypass was employed with continuing demonstrations of its safety and efficacy in treating various life-threatening conditions, including respiratory failure necessitating bronchopulmonary lavage. One report [29] described the successful use of cardiopulmonary bypass (standard) to temporarily support cardiac dysfunction secondary to drug overdose.

Table 3-3. Limitation of CPS 1958–1985

1. Rapid, safe vascular access
2. Rapid, safe perfusion circuit setup and operation
3. Technical support
4. Safe and effective circulatory/respiratory support

Another category of patient frequently found in the literature, for whom CPS was (and still is) most often misapplied, is that of refractory cardiac arrest. Only the rarest of anecdotal reports have included case studies of successfully resuscitated patients who had suffered cardiac arrest and received extended periods of cardiopulmonary resuscitation (CPR). Since Kouwenhoven [30] first described the technique, CPR has been the most widely applied therapy for cardiac arrest. Yet, even under controlled conditions, only 10–15% of patients receiving CPR survive [31]. The prognosis for patients subjected to CPR procedures for over 30 minutes is extremely poor. Late intervention with CPS after CPR rarely results in measurable patient benefit.

The state-of-the-art cardiopulmonary bypass technology available to the practitioners of CPS between 1958 and 1985 did not allow for the uniform attainment of the four key operational necessities (Table 3-3) for successful CPS implementation in a variety of settings.

Having evolved in the cardiac surgical suite, femoro-femoral cannulation for cardiopulmonary bypass was performed by cardiac surgeons through a vascular cutdown. This approach to preparing a patient for CPS had inherent limitations that restricted access to this technology to many patients. The most significant limitation was that a patient was required to be in the general vicinity of a cardiovascular surgeon. Another limitation was the speed with which the surgical procedure necessary to place the cannulae could be performed. Both of these issues limited access to patients in whom CPS could be used.

Even after the cannulae had been inserted, difficulties in achieving and maintaining the blood flow rates necessary to sustain a patient remained. This problem was attributable to two phenomena: low internal diameter/outer diameter (ID/OD) cannula dimension ratio and low siphon pressures. The low ID/OD cannula dimension ratio created resistance to blood flow, which could not be overcome by the inadequate siphon (gravity fed) drainage mechanism employed to evacuate venous blood from the vena cavae and right atrium. Siphon drainage is incapable of generating enough negative pressure to adequately decompress the myocardium or aspirate a volume of blood sufficient to support normal systemic blood flows through femoral cannulae that are small enough to be easily inserted. Larger cannulae were necessary to maximize blood flow, but created other hemodynamic complications, such as limb and hepatic congestion. Additionally, the large cannulae sometimes resulted in vascular trauma, including dissection.

The perfusion circuits used in the past were complicated, time consuming,

and potentially hazardous, especially in emergency circumstances under which the majority of CPS cases were performed. The equipment then used was comprised of an assemblage of blood tubings, an artificial lung, and a blood pump, which were best suited to elective cardiac surgical procedures performed within the controlled environment of an operating room. One manufacturer, Travenol Laboratories, Inc., in 1969 created a portable heart-lung machine consisting of an occlusive blood pump, heat exchanger, and sheet-type bubble oxygenator holder on a compact movable frame. Known as the EPO, it was used with great success by a few investigators [5–7].

Unfortunately, for the balance of physicians desirous of initiating a CPS program, the perfusion circuits of the time still required a cumbersome and time-consuming aseptic procedure to assemble. Once assembled, the circuits required meticulous and time-consuming priming so that no air remained within the blood tubings. Membrane oxygenators typically were more difficult and required longer periods of time to prime than did bubble-type oxygenators. Although faster to prime, bubble oxygenators had venous blood reservoirs open to the atmosphere, which presented a significant risk to patients. Such open venous reservoirs, especially when used with positive displacement roller pumps, required unfailing diligence to avoid the delivery of a massive intraarterial air embolus secondary to an emptied venous reservoir. Since many CPS patients were transported from the site of cardiac or pulmonary failure to a treatment location, unavoidable "sloshing" would occur in the venous reservoir, increasing the likelihood of air entering the arterial circuit. Compounding the risks associated with bypass management, both bubble oxygenators and membrane oxygenators with venous reservoirs demanded a continuous level of concern for the dynamic volume shifts that could alternately and unexpectedly fill and empty the venous reservoir secondary to changes in the patient's systemic vascular resistance or capacitance. This would unnecessarily expose the patient to additional risk.

Primarily due to the complexity and potentially hazardous nature of the equipment needed to perform cardiopulmonary bypass, the responsibility for operating the heart-lung machine was delegated only to appropriately trained perfusion technicians. This was uniformly true for elective applications of CPS. Until 1985, there were no portable CPS devices capable of safely and routinely supporting normal adult blood flow rates and the supernormal gas exchange requirements usually encountered during resuscitation procedures.

PRESENT STATUS

In 1985, C.R. Bard, Inc. (Tewksbury, MA) introduced a portable heart-lung machine and its associated perfusion circuit and percutaneous femoral bypass cannulae that addressed the limitations of prior systems. As soon as the Bard CardioPulmonary Bypass Support (CPS^{TM}) system became commercially available, a reevaluation of potential applications for CPS was initiated.

TECHNOLOGY

After years of development, the Bard CPS system was released for clinical use. The system is composed of three elements:

- a femoro-femoral percutaneous cannulation kit
- a portable, self-contained heart-lung machine
- a preassembled perfusion circuit

The limitations of surgically inserted cannulae discussed earlier were overcome by the use of large-bore, thin-wall, extruded Teflon® cannulae. Available in 20 Fr and 18 Fr for both arterial and venous insertion over a guidewire with a modified Seldinger technique [32,33] further refined by Shawl [34], the cannulae can be inserted safely in under 3 minutes. The cannula sheaths have a large ID/OD ratio, which minimizes pressure drop across the length of the catheters and results in a significantly reduced resistance to blood flow.

This development in femoral bypass cannulae was important for several reasons. First, it allowed for rapid vascular access in two different ways. The technique developed by Shawl for cannulae insertion was much faster than a surgical cutdown procedure, facilitating the use of CPS within the narrow constraints of the "therapeutic window" available for any particular patient. Furthermore, a vascular cutdown required the availability of a surgeon.

The CPS cannulae, because of their configuration and the perfusion circuit to which they are attached, allow the generation of 5–6 l/min of blood flow through a single venous and single arterial cannula. This was a major contribution to the efficacy of CPS.

The only significant hardware development not fully exploited in past applications of CPS was that of the nonocclusive (constrained vortex, centrifugal) blood pump. The physics governing the operation of nonocclusive blood pumps has distinct advantages over positive displacement pumps in three important areas [35,36] (Table 3-4).

Each of these advantages has special significance when used in the setting of isovolemic CPS. Blood pumps that are preload and afterload sensitive protect the patient from unneccessary exposure to risks associated with changes in venous return or arterial line competency. Relying on fluid inertia generated by friction-driven centrifugal forces to achieve flow, a significant loss of continuity between the pump drive component and blood, such as would occur if a massive volume of air was aspirated into the pump, would disable the

Table 3-4. Advantages of nonocclusive blood pumps

1. Preload and afterload sensitivity
2. Inability to pump a large bolus of air
3. Less formed-blood-element damage over time

pumping mechanism and avoid a potential intra-arterial air embolus. The physics of this type of pump also result in less formed element damage than a standard roller-type pump.

Of the four key features CPS perfusion circuits should include, the most critical is an air-trapping capability. Any CPS perfusion circuit must incorporate a membrane oxygenator capable of functioning as a gaseous microembolus and gross air trap. Since an arterial line filter is impossible to adequately prime under the most urgent of circumstances (such as emergency CPS), the oxygenator must assume this role. Gas-trapping capabilities are utilized extensively during the preoperative priming of the circuit. Equally important is the ability to remove air from the perfusion circuit intraoperatively should air inadvertently enter the blood pathway.

The oxygenator must also be capable of exchanging exceptional volumes of respiratory gases. Since CPS is often used for resuscitation, and patients in cardiac arrest typically have profoundly depressed venous oxygen saturations and exceptionally high venous carbon-dioxide levels, the ideal oxygenator should have the ability to normalize patient blood gases in a short period of time.

Another requirement for full-flow CPS is an isovolemic perfusion circuit, or more specifically, a perfusion circuit without a capacitive reservoir. For standard CPB, venous blood is withdrawn from the patient utilizing a siphon principle. The magnitude of siphon pressure is dependent upon the height differential between the patient's right atrium and a variable capacity venous reservoir. Blood is then actively pumped out of the reservoir through an oxygenator and back to the patient. This configuration for a CPS application cannot support the normal blood flow requirements of patients in cardiac arrest because the higher resistance (compared to standard transthoracic bypass cannulae) femoral cannulae limit the volume of blood that can be passively drained into the reservoir. High-flow CPS requires that blood be actively aspirated out of the right atrium via a nonocclusive blood pump, precluding the incorporation of a reservoir between the venous cannula and the blood pump. The absence of a reservoir in the circuit also simplifies the perfusion procedure by eliminating the intraoperative variable of "fluid shift" between the patient and the perfusion circuit. It also limits the hazards associated with venous reservoirs as described previously in relationship to air safety.

Necessary elements of the modern perfusion circuit are shown in Table 3-5.

Table 3-5. Critical CPS circuit characteristics

- Air and gaseous microembolus filtration
- Exceptional respiratory gas transfer capabilities
- Isovolemic perfusion circuit with nonocclusive blood pump
- Redundant safety features

APPLICATIONS

Hemodynamic stability with normal blood flows and blood gas delivery to otherwise ischemic tissues have made CPS a viable temporary life-support technology that acts as a therapeutic adjunct.

The most frequent indication for initiating CPS is the need "to buy time." In instances where a patient presents *in extremis*, the immediate institution of CPS allows the medical staff to mobilize the resources and expertise necessary to work up the patient diagnostically, and then initiate treatment or transport the patient to a location where definitive therapy can be administered. While on CPS, multi-organ system failure secondary to extended periods of hypotension or hypoxia is avoided.

The first reported successful employment of the Bard CPS system was in a patient resuscitated from profound accidental hypothermia [37]. Successful resuscitation was defined as a patient discharged from the hospital with normal mentation and physiologic status who is a long-term survivor. Built on a historically sound foundation [19–22, 38–40], and followed by several other reports [41–43] including a U.S. Army Medical R&D Command Conference [44], cardiopulmonary bypass is often the treatment of choice in those instances where rapid core rewarming is indicated.

Between early 1988 and late 1989, numerous citations [45–63] appeared in the medical literature describing experiences with and indications for the use of CPS in and around the cardiac catheterization laboratory. The area in which the majority of CPS procedures are being performed is prophylactic use for hemodynamic support during high risk interventional procedures.

The newest procedure, coined *supported angioplasty*, electively supports patients with cardiopulmonary bypass in anticipation of a significant incremental risk to the patient during coronary angioplasty. Although specific indications for CPS in the setting of high risk angioplasty vary somewhat, there is general agreement on the "supported angioplasty" patient selection criteria detailed by Shawl (Chapter 6).

Technically, a PTCA procedure is facilitated by reducing operator anxiety while treating a patient who is at significant risk for hemodynamic collapse. Complete circulatory support provided by full-flow CPS provides a "safety net" for the patient should an undesirable event ensue.

When indicated, supported angioplasty allows for markedly extended balloon inflation times [52], with all the attendant advantages and none of its hemodynamic liabilities. Though the definitive conclusion regarding the impact of greatly extended balloon inflation times has yet to be drawn, the option to utilize them is now facilitated.

Typical signs of myocardial ischemia caused by balloon inflation include angina and ST-segment shifts. During CPS supported angioplasty, these signs are significantly reduced or completely eliminated. This suggests that CPS bypass is able to reduce myocardial oxygen consumption and increase the myocardial ischemic tolerance time enough to accommodate an extended balloon inflation time.

Should the patient experience ventricular fibrillation or other nonperfusing dysrhythmia, the ability to fully support systemic circulation and normal hemodynamic parameters gives the interventionalist the opportunity to address the etiology of the rhythm disturbance in a patient who is conscious and comfortable without the obligatory distraction of a major CPR resuscitation procedure.

Procedures such as valvuloplasty [47,48,54], mechanical atherectomy [50], and cardiopulmonary resuscitation outside of the cardiac catheterization laboratory [37,57,58] have been made safer and more effective when used in concert with CPS. As a heart-lung machine apparatus, it can substitute entirely, though temporarily, for all intrinsic cardiac and pulmonary functions.

FUTURE DIRECTIONS

Improvements in CPS technology will include the development of smaller, lighter, multifunction hardware systems that will facilitate the transport of patients on bypass from one location to another. These microprocessor-based hardware systems will also be capable of performing tasks other than supporting systemic circulation, such as scavenging shed blood, monitoring and automatically adjusting blood flow and blood gas controls, and delivering pharmacologic "cocktails" to assist in organ preservation.

Vascular access techniques and products have already evolved through several generations. Future developments will undoubtedly refine materials selection, physical characteristics, and functional scope. Areas of interest from an operational perspective include multilumen cannulae, allowing simultaneous monitoring, sampling, left ventricular venting, and therapeutic device insertion (e.g., angioplasty balloon, laser catheter). It is conceivable that the insertion procedure could be simplified to a degree that would allow a highly trained paramedical specialist to implement CPS in remote locations (in critical circumstances) as a means of stabilizing patients for transport to a medical facility.

Perfusion circuits are likely to undergo improvements in the areas of size, adaptability, and convenience. Improvement in performance characteristics, such as gas exchange efficiency and gaseous microembolus filtering, are inevitable. The perfusion circuits of the future will be electronically and mechanically interfaced with microprocessor-based hardware, allowing for hands-off operation. This will allow the operator to function with less anxiety and thereby improve the safety of the procedure.

CONCLUSION

Femoro-femoral cardiopulmonary bypass has evolved into a clinically useful technique since 1957 [65]. Advances in technology have accelerated the use of CPS outside the cardiac surgical suite. There has been an evolution of equipment from crude vascular cannulae requiring surgical insertion and perfusion equipment scarcely adequate for its intended purpose in the operating room,

to the currently available full-flow cardiopulmonary bypass through percutaneously installed cannulae.

REFERENCES

1. Gibbon JH. Application of a mechanical heart and lung apparatus to cardiac surgery. *Minn Med* 1954; 37:171.
2. Stuckey JH, Newman MM, Dennis C, et al. The use of the heart-lung machine in selected cases of acute myocardial infarction. *Surg Forum* 1958; 8:342–344.
3. Newman MM, Stuckey JH, Levowitz BS, et al. Complete and partial perfusion of animal and human subjects with the pump-oxygenator. *Surgery* 1955; 38:30.
4. Cooley DA, Beall AC, Alexander JK. Acute massive pulmonary embolism — Successful surgical treatment using temporary cardiopulmonary bypass. *JAMA* 1961; 177(5):283–286.
5. Mattox KL, Beall AC. Extending the art: Portable cardiopulmonary bypass. *J Am Coll Emerg Physicians* 1975; 4(6):528–531.
6. Mattox KL, Beall AC. Resuscitation of the moribund patient using portable cardiopulmonary bypass. *Ann Thorac Surg* 1976; 22(5):436–442.
7. Mattox KL, Beall AC. Application of portable cardiopulmonary bypass to emergency instrumentation. *Med Instru* 1977; 11(6):347–349.
8. Joseph WL, Maloney JV Jr. Extracorporeal circulation as an adjunct to resuscitation of the heart. *JAMA* 1965; 193(8):117–118.
9. Kennedy JH. The role of assisted circulation in cardiac resuscitation. *JAMA* 1966; 197(8): 97–100.
10. Danielson GK, Hasbrouck JD, Bryant JR. Cannulation under local or regional anesthesia for the "salvage" cardiac patient. *J Thorac Cardiovasc Surg* 1968; 55(6):864–872.
11. Gil-Rodriguez JA. Emergency extracorporeal circulation. *Int Anesthesia Clin* 1969; 7:921–932.
12. Kennedy JH. Assisted circulation: An extended concept of cardiopulmonary resuscitation. *J Cardiovasc Surg* 1969; 57:688–701.
13. Lande AJ, et al. Clinical experience with emergency use of prolonged cardiopulmonary bypass with a membrane pump-oxygenator. *Ann Thorac Surg* 1970; 10:409–421.
14. Kennedy JH, Bricker DL. Criteria for selection of patients for mechanical circulatory support. *Am J Cardiol* 1971; 27:33–40.
15. May IA, Hardy KL, Samson PC. Emergency bypass for the community. *Am J Surg* 1971; 122:256–259.
16. Lefemine AA, Harken DE. Extracorporeal support of the circulation by means of venoarterial bypass with an oxygenator. *J Thorac Cardiovasc Surg* 1971; 62:769–780.
17. Baird RJ, et al. Assisted circulation following myocardial infarction: A review of 25 patients treated before 1971. *Can Med Assoc J* 1972; 107:287–291.
18. Berger RL, Saini VK, Dargan EL. Clinical applications of femoral vein-to-artery cannulation for mechanical cardiopulmonary support and bypass. *Ann Thorac Surg* 1973; 15:163–169.
19. Towne WD, et al. Intractable ventricular fibrillation associated with profound accidental hypothermia — Successful treatment with partial *cardiopulmonary* bypass. *N Engl J Med* 1972; 287:1135–1136.
20. Fell RH, Gunning AJ, Bardhan KD, et al. Severe hypothermia as a result of barbiturate overdose complicated by cardiac arrest. *Lancet* 1968; 1:392–394.
21. Kugelbert J, Schuller H, Berg B, et al. Treatment of accidental hypothermia. *Scand J Thorac Cardiovasc Surg* 1967; 1:142–146.
22. Davies DM, Miller EJ, Miller IA. Accidental hypothermia treated by extracorporeal blood-warming. *Lancet* 1967; 1:1036–1037.
23. Phillips SJ, et al. Percutaneous initiation of cardiopulmonary bypass. *Ann Thorac Surg* 1983; 36:223–225.
24. Winton TL, Salerno TA. Femorofemoral bypass for temporary cardiac support in heart surgery. *Can J Surg* 1983; 26:465–468.
25. Zapol WM, et al. Venovenous bypass with a membrane lung to support bilateral lung lavage. *JAMA* 1984; 251:3269–3271.
26. Freedman AP, Pelias A. Alveolar proteinosis lung lavage using partial cardiopulmonary bypass. *Thorax* 1981; 36:543–545.
27. Seard C, Wasserman K. Simultaneous bilateral lung lavage (alveolar washing) using partial

cardiopulmonary bypass. *Am R Respiratory Dis* 1970; 101:877–884.
28. Altose MD, Hicks RE, Edwards MW. Extracorporeal membrane oxygenation during bronchopulmonary lavage. *Arch Surgery* 1976; 111:1148–1153.
29. Noble J, et al. Massive lidocaine overdose during cardiopulmonary bypass. *Br J Anes* 1984; 56:1439–1441.
30. Kouwenhoven WB, Jude JR, Knickerbocker GG. Closed-chest cardiac massage. *JAMA* 1960; 173:1064–1067.
31. Bedell SE. Survival after cardiopulmonary resuscitation in the hospital. *N Engl J Med* 1983; 309:569–576.
32. Seldinger, SI. Catheter placement of the needle in percutaneous angiography: A new technique. *Aeta Radiol* (Stockholm) 1953; 39:368.
33. Conahan TJ, Schwartz AJ, Geer RI. Percutaneous catheter introduction: A Seldinger technique. *JAMA* 1977; 237:446.
34. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous institution of cardiopulmonary (bypass) support: Technique and complications. *J Am Coll Cardiol* 1989; 13:159A.
35. Oku T, Harasaki H, Smith W, Nose Y. Hemolysis — A comparative study of four nonpulsatile pumps. *ASAIO Trans* 1988; 34(3):500–504.
36. Lynch MF, Hammond C, Schmidt WR, et al. *Kinetic Heart Pumping.* Biomedicus, Inc., Minneapolis, MN.
37. Hauty MG, Esrig BC, Hill JG, Long WB. Prognostic factors in severe accidental hypothermia: Experience from the Mt. Hood tragedy. *J Trauma* 1987; 27(10):1107–1112.
38. Wickstrom P. Accidental hypothermia: Core rewarm with partial CPB. *Am J Surg* 1976; 131:622–625.
39. Dorsey JS. V-A bypass in hypothermia [letter]. *JAMA* 1980; 244:1900
40. Seuffert, C. An Alaskan experience with CPB in resuscitation. *Alaska Med* 1984; 26:31–33.
41. Manart, FD. The role of EC bypass in management of accidental hypothermia. *Ann Th Surg in Pers* 1987; 86:123–130.
42. Maresca, L. Treatment of hypothermia by ECC and internal rewarming. *J Trauma* 1987; 27:89–90.
43. Cohen DJ. Resuscitation of hypothermia PT. *Am J Emerg Med* 1988; 6:475–478.
44. Medical After Action Conference, Mount Hood, 1986 Byasss Re-Warming, U.S. Army Res Inst of Environ Med. 1988.
45. Vogel RA, Tommaso CL, Gundry SR. Initial experience with coronary angioplasty and valvuloplasty using semipercutaneous cardiopulmonary support. *Am J Cardiol* 1988; 62: 811–813.
46. Kantor KR. Emergency resuscitation with ECMO for failed angioplasty. *J Am Coll Cardiol* 1988; 11:149A.
47. Vogel RA. The Maryland experience: Angioplasty and valvuloplasty using percutaneous cardiopulmonary support. *Am J Cardiol* 1988; 62:11K–14K.
48. Vogel RA, Tommaso CL, Gundry SR. Initial experience with coronary angioplasty and aortic valvuloplasty using elective semipercutaneous cardiopulmonary support. *Am J Cardiol* 1988; 62:811–813.
49. Kolobow T, Rossi F, Borelli M, Foti G. Long-term closed chest partial and total cardiopulmonary bypass by peripheral cannulation for severe right and/or left ventricular failure, including ventricular fibrillation. *Trans Am Soc Artif Intern Organs* 1988; 34:485–490.
50. Muller DWM, Ellis SG, Topol EJ. Athrectomy of the left main coronary artery with percutaneous cardiopulmonary bypass support. *Am J Cardiol* 1989; 64:114–116.
51. Sundram P, Harvey JR, Johnson RG. Benefit of the perfusion catheter for emergency coronary artery grafting after failed percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1989; 63:282–285.
52. Vogel JHK, et al. Percutaneous (nonsurgical) supported angioplasty in unprotected left main disease and severe left ventricular dysfunction. *Clin Cardiol* 1989; 12:297–300.
53. O'Neill P, et al. Prolonged ventricular fibrillation — Salvage using a new percutaneous cardiopulmonary support system. *Am J Cardiol* 1989; 545.
54. Shawl FA, Percutaneous cardiopulmonary bypass support in high risk interventions. *J Inv Cardiol* 1989; 64:287–291.
55. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous cardiopulmonary bypass support in high-risk patients undergoing percutaneous transluminal coronary angioplasty.

Am J Cardiol 1989; 64:1258–1263.
56. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Emergency percutaneous cardiopulmonary bypass with cardiogenic shock from acute myocardial infarction. *Am J Cardiol* 1989; 64:967–970.
57. Overlie DA, Riechman RT, Smith SC, Debitsky W, Adamson RM, Jaski RE, Marsh DG, Daily PO. Emergency use of portable cardiopulmonary bypass in patients with cardiac arrest. *J Am Coll Cardiol* 1989; 13:160A.
58. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous cardiopulmonary bypass to support high risk elective coronary angioplasty. *J Am Coll Cardiol* 1989; 13(2):160A.
59. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Cardiopulmonary bypass supported coronary angioplasty in inoperable patients. *J Am Coll Cardiol* 1989; 13:59A.
60. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Emergency percutaneous cardiopulmonary (bypass) support in cardiogenic shock. *J Am Coll Cardiol* 1989; 13(2):160A.
61. Shawl FA, Domanski MJ, Wish M, Punja S, Hernandez TJ. Emergency percutaneous cardiopulmonary bypass in patients with cardiac arrest. *Circulation* 1989; 80(4; Suppl. II):II-271.
62. Shawl FA, Domanski MJ, Wish M, Punja S, Hernandez TJ. Cardiopulmonary bypass supported PTCA: Experience in 75 high risk patients. *Circulation* 1989; 80(4; Suppl. II):II-271.
63. Shawl FA Domanski MJ, Wish M, Davis M, Punja S, Hernandez TJ. Bypass support in patients with cardiac arrest in the catheterization laboratory. *Cathet Cardiovasc Diag* 1990; 19:8–12.
64. Litzie AK, Roberts CP. Emergency femoro-femoral cardiopulmonary bypass. *Proc Am Acad CV Perfusion* 1987; 8:60–65.

4. BASIC PRINCIPLES OF CARDIOPULMONARY BYPASS

GEORGE A. JUSTISON

INTRODUCTION

The development of percutaneous femoral-femoral cardiopulmonary bypass (CPB) offers new opportunities for treatment of the failing myocardium [1]. By eliminating the time-dependent task of vascular exposure required for conventional cannulation, a new group of patients who were previously excluded can receive the benefit of total CPB [2]. The application of closed-chest femoral-femoral bypass, although related to the more traditional form of CPB, requires a new level of diagnostic and management skills by the clinician. New challenges are presented by percutaneous CPB due to the change in the patient profiles and procedures performed.

The objective of this chapter is to introduce the basic principles of cardiopulmonary bypass to the clinician. A thorough understanding of the integration of the extracorporeal circuit (ECC) is necessary for proper patient management. This chapter will provide an introduction to the physiology involved in the operation of extracorporeal systems and how it impacts on patient care. The following discussion is intended to apply specifically to normothermic femoral veno-arterial CPB.

GETTING STARTED

Prior to the initiation of CPB or any invasive mechanical support procedure, it is important that the clinician have a complete medical history (Table 4-1). This preparation is important in the successful planning and implementation

Table 4-1. Patient data collection: Patient information that should be collected prior to the initiation of cardiopulmonary bypass

- Prior medical history
- Prior surgical history
- Blood chemistry
- Height
- Weight
- Current medications
- Vascular studies

of CPB. Information that should be gathered includes blood chemistry data, allergies, current medications, previous medical history and risk factors, as well as physical examination findings. Of particular importance is a history of aortic aneurysm, dissection, unusual bruits, and prior surgery.

Height, weight, and body surface area (BSA) must be ascertained prior to implementation of CPB. BSA may be calculated as follows [3]:

$$\text{BSA } (m^2) = 0.007184 \times \text{weight } (kg)^{0.425} \times \text{height } (cm)^{0.725}.$$

Knowledge of the BSA is important in the estimation of the extracorporeal blood flow necessary to support the patient. Once a thorough review of the patient's record has been completed, the physician and perfusionist can begin to utilize these data in the planning of the CPB support strategy.

FLUID MANAGEMENT

Fluid management is of vital importance in the setting of total CPB. Estimation of total circulating blood volume can be difficult when using a closed noncapacitive extracorporeal circuit due to the lack of a volume storage reservoir [4]. Use of such a system requires the patient's venous vasculature to act as the volume storage reservoir during the procedure. In order to estimate the volume in the vascular system, the physician must determine the central venous pressure or pulmonary artery pressures and take into account the operating characteristics of the ECC. Limitations exist in the ability to estimate the vascular volume due to mechanical influences [4]. Failure to maintain a minimum operating volume will result in failure to achieve the desired blood flow. Overhydration can result in severe hemodilution and excessive extravascular volume shifts. Factors that affect fluid shifts during CPB include temperature, flow rates, hemodilution, constituents of the priming solution, capillary permeability, and urine output [5].

The reduction of hemoglobin concentration through the addition of nonhemoglobin-containing solutions is termed *hemodilution*. Hemodilution has both inherent risks and benefits for the patient undergoing CPB. Through the use of crystalloid priming solutions, we are able to reduce the dependence on homologous blood products and the risk associated with the use of these

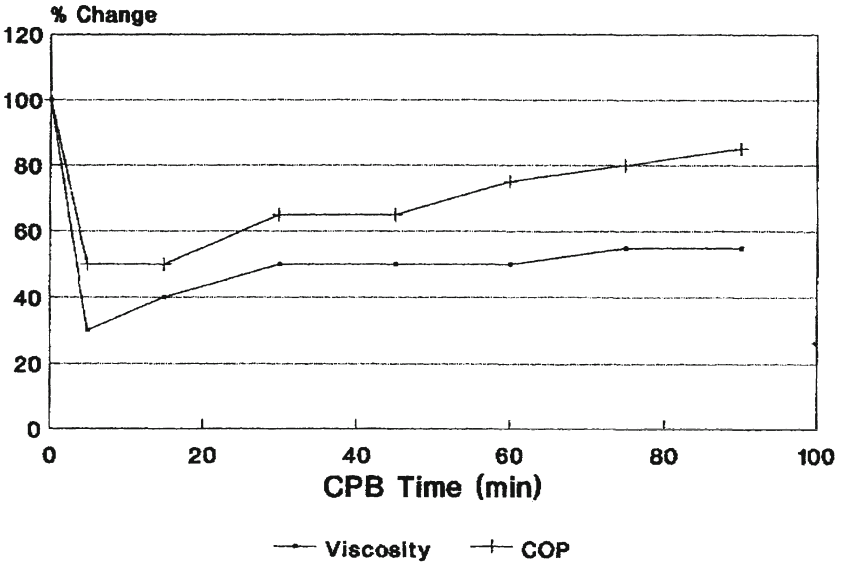

Figure 4-1. Viscosity/COP. The blood viscosity and colloid oncotic pressure changes associated with hemodilution during CPB. Adverse changes may be controlled through limited hemodilution and appropriate volume supplements. COP = colloid oncotic pressure.

components [8,12]. Hemodilution will reduce the viscosity of the circulating blood supply and increase capillary bed perfusion, especially during periods of nonpulsatile flow. Excessive hemodilution, on the other hand, can increase extravascular volume, reduce the oxygen carrying capacity of the blood, and reduce the viscosity to the point of adversely affecting the ability to maintain an adequate perfusion pressure [4,8,12]. A typically tolerable range for hemodilution during CPB is 7–9 g%.

During the initiation of CPB a drop in the mean arterial pressure (MAP) often occurs. This drop may be due to the sudden decrease in viscosity upon introduction of the crystalloid prime volume. As bypass progresses the MAP will gradually increase, partly due to the increased viscosity (Figure 4-1) as the circulating blood volume and the prime become homogenous, and increasing extravascular fluid shifts occur.

The goal of fluid addition is to add volume to the intravascular space without significantly altering the blood chemistry. When selecting the type of solution (Table 4-2) for CPB, four options should be available to the clinician. Crystalloid solutions, which are the major priming and volume replacement agent during CPB, should contain normal electrolyte values and have a pH adjusted to 7.4 to minimize buffer base effect. In addition, some type of

Table 4-2. Solution list: Solutions that should be available for CPB priming and volume replacement

- Balanced electrolyte solution
- 5% and 25% albumin
- Mannitol
- Hetastarch
- Low molecular weight dextran

Table 4-3. Volume selection: Physiologic factors to consider when selecting volume replacement therapy

- Hemoglobin concentration
- Osmolarity
- Colloid oncotic pressure

hyperosmotic and hyperoncotic solution should be available for control of the blood osmolarity and oncotic pressure (Table 4-3) when excessive crystalloid administration is required. Control of the colloid oncotic pressure and blood osmolarity is critical in controlling the degree of extravascular fluid shift commonly associated with CPB. This is especially evident in the application of CPB in resuscitation of the cardiac arrest patient who is unresponsive to conventional volume addition resuscitation. Several common solutions utilized are Hetastarch solutions and varying concentrations of serum albumin solutions. The fourth product that should be made available is either autologous or homologous red cell products for their oncotic and hemoglobin benefit.

An estimation as to the degree of hemodilution that will occur can be made by calculating the postdilution hematocrit. This values estimates the hematocrit value after the asanguineous prime has become homogenous with the patient's circulating blood volume. Calculation of this value will aid the perfusionist and responsible physician in determining if blood component therapy is indicated. Using the post dilution estimator developed by Fletcher, we can determine the estimated blood volume (EBV) from the patient's body surface area using the following formula [13]:

$$\text{EBV} = 0.416 \times (\text{height [cm]})^{0.3} + 0.039 \times (\text{weight [kg]}) - 0.03.$$

The post dilution hematocrit may then be calculated using the simple ratio:

$$\text{HCT}_{\text{post}} = \frac{(\text{EBV} \times \text{HCT}_{\text{pre}})}{(\text{D} + \text{EBV})},$$

where HCT_{post} = postdilutional hematocrit, HCT_{pre} = hematocrit predilution (%), EBV = estimated blood volume (ml), and D = dilutional volume (ml).

The usefulness of the circulating blood volume calculation, however, can be affected by the specific cardiac pathology present. Patients with congestive heart failure may present with an increased extracellular and red blood cell volume. This phenomena may also be present in patients with valvular dysfunction and acts as a compensatory mechanism for the reduced cardiac performance. Patients with chronic coronary artery disease may see a reduced circulating volume if ventricular performance is still normal. It is postulated that the reduction in circulating blood volume in these patients is the result of increased sympathetic stimulation in these patients [12,13].

Estimation of the need for volume replacement during CPB can be made through the simultaneous analysis of central venous pressure, inlet resistance to the ECC, and pump RPM settings [4]. If hypovolemia exists, the operator will notice a stable or decreasing blood flow with increasing pump RPM.

Excessive circulating volume and hemodilution are problems that often occur during CPB, especially when femoral veno-arterial bypass is used in cardiac arrest. Several options are available to the clinician for the reduction of circulating volume and correction of excessive hemodilution. The first and most physiologic method is to promote an increase in diuresis. This is often a secondary result of increased renal blood flow during CPB. However, if diuresis is still not adequate, diuretic therapy may be indicated. A general rule for minimum diuresis during CPB is 1 ml urine/kg/hr. Two other extracorporeal procedures available to the clinician for volume control are autologous centrifugal cell washing and ultrafiltration [13,14]. Centrifugal cell washing has the advantage of being rapid and allowing significant changes in hematocrit, but in this technique plasma and platelet components, which are necessary for postprocedure hemostasis, are lost. Ultrafiltration removes plasma water and some low molecular weight substances, and is generally slower at reversing hemodilution.

Two other effects of hemodilution encountered during CPB are the reduction in coagulation proteins and platelet concentrations. The reduction of these important constituents of coagulation is the result of two interactions unique to extracorporeal devices. The first is crystalloid hemodilution caused by the asanguineous priming solution that results in reduction of red blood cell concentration. Through the application of the postdilution hematocrit equation described above, the clinician can also estimate the proportional decrease of other formed elements due to hemodilution. This will drive the decision as to the prime constituents used in preparation of the ECC. Excessive dilution of plasma proteins necessitates the addition of serum albumin to the ECC prime.

In addition to hemodilution, biocompatability of the ECC also affects the reduction of plasma proteins and platelets during ECC. Upon the first pass of blood through the ECC complex, biochemical and bioelectric events occur between the blood and the foreign surfaces found in the ECC [14]. The net result is a decrease in the concentration of circulating platelets and plasma

proteins. In addition, the mechanical stress placed on formed elements by the blood pump can significantly increase their rate of destruction. In the closed ECC system used in femoral veno-arterial bypass, the operator must carefully study the relationship between cannula selection and circuit design to minimize mechanical stress [9].

One of the most significant effects of hemodilutional crystalloid priming is the effect on interstitial water accumulation throughout the body. Of particular interest is the effect on myocardial water content. Although the total water volume involved may be small compared to other organ systems, myocardial edema associated with cardiopulmonary bypass has been shown to have a significant impact on myocardial sarcoplasmic reticulum and mitochondrial structure and function. Factors that may affect the myocardial water content include the coronary perfusion pressure, ventricular distension, multiple defibrillations, and perfusate composition [14]. In addition, reactive hyperemia associated with reperfusion may be associated with increased localized myocardial water content due to the increased capillary permeability and higher flow rates.

Retention of a relatively normal blood chemistry during CPB is one of the goals of the perfusionist. Because of the large quantities of crystalloid priming solutions used, it is possible to have rapid and dramatic changes in the blood chemistry following the initiation of CPB [6]. Serum potassium is the primary electrolyte of concern during CPB. Serum potassium during CPB can be affected by the pump prime solution, urine output, and the amount of red-cell destruction.

Most balanced electrolyte solutions used for priming have a normal concentration of potassium. This will aid in the prevention of hypokalemia due to hemodilution. Because many of these solutions were designed for use during surgical procedures, they are typically devoid of calcium, to prevent its inotropic effect. As a result, hypocalcemia is common during CPB and calcium administration may be necessary. Hyperkalemia may be the result of reduced urine output, increased red-cell hemolysis, or seen in the diabetic patient. In order to prevent arrhythmias, it important to have some method of control immediately available. This may include diuretic therapy, insulin and glucose, or cell washing.

ANTICOAGULATION

Contact of blood with the foreign surfaces found in the ECC acts as a potent stimulus for activation of the intrinsic coagulation pathway. Inadequate anticoagulation can result in clotting intravascularly and in the ECC. Clot formation can result in particulate embolization if pumped back to the patient and in the promotion of a consumptive coagulopathy [15].

It is imperative to the successful performance of CPB to monitor the status of the coagulation cascade. Several techniques used to monitor anticoagulation (Table 4-4) include the activated clotting time (ACT) and heparin-protamine

Table 4-4. Anticoagulation monitoring: Anticoagulation monitoring guidelines for CPB

- Sample frequency
  - Baseline
  - 5 minutes post-heparin
  - Every 20 minutes on bypass
- Maintain ACT >400 seconds
- ACT extended by
  - Hemodilution
  - Thrombolytics

titration (HPT). Prior to the administration of heparin, it is advantageous to determine the initial baseline coagulation status of the patient. This can serve as a basis for administration of anticoagulants prior to the initiation of CPB, and it allows the physician to asses the alterations in the normal coagulation system resulting from CPB. Monitoring of the anticoagulation status should be performed about every 20 minutes during CPB to ensure that an adequate prolongation of the coagulation time is maintained [15].

Prior to the cannulation procedure, 200–400 U/kg body weight of sodium heparin should be administered through a central venous line and allowed to circulate for a minimum of 5 minutes. At that time, a sample should be obtained and analyzed using either the ACT or HPT method. Adequate prolongation of the coagulation time for the initiation of CPB is four times the baseline sample. When using the ACT method, this equates to an ACT of approximately 400 seconds or more. If at any time, the concentration of circulating heparin should decrease during the procedure or the ACT falls below 400 seconds, additional heparin may be administered to prevent fibrin formation.

Additional heparin doses may be determined by calculating the patient's heparin response factor. The heparin response factor is simply the number of seconds the ACT was elevated by the loading does of heparin. It may be calculated by subtracting the baseline ACT from the post-heparinization ACT and dividing by the loading dose of heparin:

Heparin Factor = Heparin (units)/[Post-heparin ACT–Baseline ACT]

Multiplying the heparin response factor by the number of seconds one wishes to elevate the ACT will yield a maintenance dose based on the individual response characteristics of the patient to a unit of heparin.

Two conditions that accompany CPB that may artificially extend the coagulation time are hemodilution and hypothermia. Hemodilution extends the coagulation process by reducing the concentration of coagulation proteins and the platelet concentration. Hypothermia, though not commonly employed in elective femoral CPB applications, can increase the natural half-life of heparin through the reduction in metabolic rate, as well as delaying the coagulation cascade.

Reversal of the anticoagulation effects of heparin may be accomplished through the administration of protamine sulfate, if desired. Heparin is not reversed when CPB is used in the setting of acute coronary insufficiency or coronary intervention. To calculate the amount of protamine necessary to reverse the circulating heparin, the clinician can reverse the heparin response factor equation and multiply the number of current units of heparin available by a protamine factor [15]. Typically a protamine factor of 1.0–1.5 mg/1000 U heparin is sufficient to reverse all circulating heparin.

CARDIOPULMONARY BYPASS PATHOPHYSIOLOGY

Cardiopulmonary bypass can alter complement activation, electrolyte balance, and pulmonary function. Activation of the human complement system has been shown to occur as a result of exposure to the ECC and may explain many perfusion-related syndromes. Exposure to the biopolymers used in the construction of ECC systems results in the formation of potent inflammatory mediators. Of particular interest are the anaphylatoxins C5a and C3a. Activation of these factors can result in increased capillary permeability, increased susceptibility to infection, and increased cellular lysis.

Reduction of the overall foreign surface area will limit the amount of polymer exposure. Some investigators have suggested the use of a high albumin prime solution to coat the surface of the ECC as a method of reducing the amount of complement activation and platelet loss during CPB. Although this remains controversial, the use of hyperoncotic and hyperosmotic agents in the prime solution may limit the amount extravascular fluid shifts seen during CPB as a result of complement activation [10,14].

The ECC activation of the complement system may result in increased pulmonary capillary permeability. Pulmonary edema may be controlled by using appropriate prime components and fluids for volume replacement. Another factor that contributes to pulmonary dysfunction is leukocytosis associated with complement activation. Limitation of the blood oxygenating surface area and careful attention to the protein content of the perfusate may reduce the clinical pulmonary manifestations associated with CPB.

REFERENCES

1. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous institution of cardiopulmonary (bypass) support: Technique and complications. *J Am Coll Cardiol* 1989; 13(2):159A.
2. Riley JB, Litzie KA, Overlie PA, Justison GA, Soronen SW, Berryessa RG, Crowley JC. Supported angioplasty: A new contribution for extra-corporeal circulation technology. *JECT* 1988; 20(4):134–137.
3. Austin JW, Harner DL. The heart-lung machine and related technologies of open heart surgery. Phoenix Medical Communication, Phoenix, AZ, 1986.
4. Justison GA, Pelley W. Hemodynamic management during closed circuit percutaneous cardiopulmonary bypass. In *27th Proced. JECT* 1989, pp. 88–95.
5. Riley JB, Young MR, Kauffman JN, Rigatti RL, Facer DL, Daly WL, Walker CT, Williams MK. In line oxygen saturation monitor. *JECT* 1983; 15(2):54–58.
6. Justison GA, Parsons S. Improved quality control utilizing continuous blood gas monitoring and computerized perfusion systems. In *27th Proced. JECT, 1989*, pp. 83–87.

7. Riley JB, Palmer-Steele CL. Hemoglobin P50 dynamics during hypothermic cardiopulmonary bypass. *JECT* 15(6):167–170.
8. Riley JB, Heinemann SO, Cavanaugh DS. Technique to give relevance to calculated oxygen transfer during cardiopulmonary bypass. *JECT* 1983; 15(2):35–40.
9. Noe MA, Riley JB, Litzie KA, Pope T, Soronen SW, Crowley JC. In vitro analysis of the physical characteristics of femoral bypass cannula. In *27th Proced. JECT, 1989*, pp. 67–75.
10. Reed CC, Stafford TB. *Cardiopulmonary Bypass*. Texas Medical Press Inc., Houston, TX, 1985.
11. Justison GA, Wagner GP, Riley JB. Ventilation technique for CPB patients less than 10 kilograms employing a 1.6 m hollow fiber membrane. *JECT* 16(3):95–101.
12. Little RC. *Physiology of the Heart & Circulation*. Year Book Medical Publishers, Chicago, 1981.
13. Fletcher RW. A model for estimating post-dilution hematocrit with minimal blood loss. *JECT* 20(3):89–91.
14. Utley JR, Stephens DB. Fluid balance during cardiopulmonary bypass. In *Pathophysiology and Techniques of Cardiopulmonary Bypass*, Vol.II. Williams & Wilkins, Baltimore, 1983.
15. Holt DW, Dumond DA, Bartosik J, Landis GH, Hardin SB, Miller M. Hemofiltration as an adjunct to cardiopulmonary bypass for total oxygenator volume control. *JECT* 14(3): 373–377.
16. Dearing JP. Activated clotting times versus protocol anticoagulation management. *JECT* 15(1):17–19.

5. ECHOCARDIOGRAPHIC AND HEMODYNAMIC CHANGES DURING PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT

JAMES A. RONAN, JR. AND FAYAZ A. SHAWL

INTRODUCTION

Cardiopulmonary bypass support has been used for 35 years in open-heart surgery to permit temporary but complete bypass of the heart and lungs while heart function is totally suspended during surgery. In that surgical setting, the heart is totally excluded from the circulation and the entire systemic blood flow is provided by the heart/lung machine. In the past few years, femero-femoral cardiopulmonary bypass support (CPS) has been used to temporarily support a patient during a period of circulatory collapse, either due to acute myocardial infarction or cardiogenic shock [1–3]. Only recently, CPS has been used to temporarily support certain high risk patients while they are having coronary angioplasty or valvuloplasty [4,5].

When total cardiopulmonary bypass is used in open-heart surgery, various supplementary measures are routinely used to preserve the myocardium, such as hypothermia and cardioplegic solutions. Furthermore, the energy requirements of the myocardium due to cardiac contraction are abruptly diminished when the cardiac rhythm ceases and the heart is at rest. On the other hand, when partial CPS is used at the time of angioplasty, the heart rhythm is maintained and no drugs or hypothermia are used to alter myocardial metabolism, so that partial CPS reduces, but does not eliminate, the energy requirements of the myocardium.

The purpose of this study was to determine the effect of CPS on cardiac function by correlating simultaneous hemodynamic pressure measurements and echocardiographic images before and during CPS.

METHOD

Ten patients with severe coronary artery disease had two-dimensional and M-mode echocardiograms performed in the cardiac catheterization laboratory after the arterial and venous cannulas had been placed for CPS, but before the CPS had been started. The patients' ages ranged from 45 to 71 years. All had previous myocardial infarctions, and all had segmental wall motion abnormalities on echocardiography. They were all in a normal sinus rhythm. Two had mild mitral regurgitation and two had moderate mitral regurgitation. Four had Doppler echocardiographic evidence of mild aortic regurgitation, but none had a murmur of aortic regurgitation. The indication for the CPS support of the PTCA was poor left ventricular function (defined as an ejection fraction <25%) and/or a target vessel that supplied greater than one-half of the remaining viable myocardium. Within 2–5 minutes after the CPS was started, the echocardiographic studies and hemodynamic measurements were repeated.

The blood flow rate on CPS was considered adequate if the pulmonary capillary wedge pressure (or pulmonary artery diastolic pressure) was ≤5 mmHg or <50% of the baseline pressure. Pump flow ranged from 2 to 4.3 l/min and averaged 3.5 l/min.

The patients were premedicated before the angioplasty, usually with 5 mg of diazepam and 50 mg of meperidine, but they were awake. The echocardiograms were performed in a slightly modified left lateral position, but because of the angioplasty the patients could not turn as far laterally as usual for a standard echocardiographic examination. Parasternal and apical two-dimensional views were recorded and Doppler studies were obtained. Measurements were made from the M-mode studies.

Pulmonary artery and pulmonary capillary wedge pressures were measured from a right-heart balloon flotation catheter, and systemic arterial pressure was monitored from a catheter in the central aorta. Pressure measurements were made simultaneously with the echocardiographic measurements.

In three selected patients, echocardiographic images were obtained during the time of balloon inflation.

RESULTS

The mean left atrial diameter decreased from 3.8 cm (range 2.9–4.4 cm) to 3.2 cm (range 2.5–3.7 cm), $p < 0.04$. Left atrial size diminished in every case on CPS (Figure 5-1 and Table 5-1).

The mean aortic root diameter increased from 3.1 cm (range 2.8–3.6 cm) to 3.3 cm (range 3.0–3.7 cm) on CPS. This increase was not significant, but it is of interest that the aortic diameter did not diminish in any patient, even though aortic pressure dropped in 8 of 10 and remained unchanged in one patient.

The mean left ventricular internal diastolic dimension (LVID) decreased from 5.6 cm (4.8–6.6 cm) to 5.1 cm (range 4.6–6.2 cm). This was not a statistically significant decrease. In two patients the endocardial images could

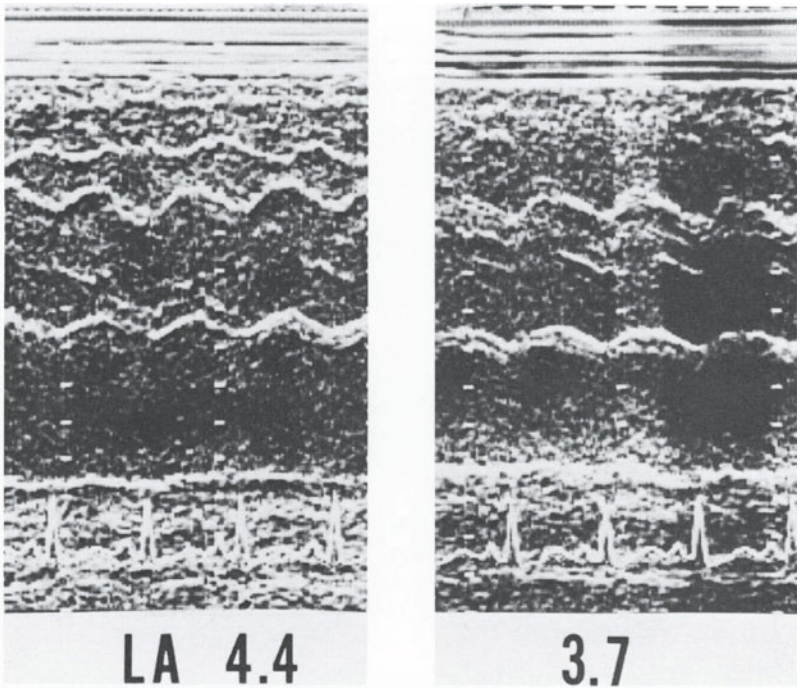

Figure 5-1. M-mode echocardiogram of left atrium and aorta before the CPS (left panel) and on CPS (right panel). Left atrial diameter decreased from 4.5 to 3.7 cm. LA = left atrium.

not be seen well enough to make the measurement in diastole, and in a third patient the measurement could not be made in systole. In only one case was the left ventricular internal diastolic dimension unchanged; in all others it diminished slightly. The mean left ventricular shortening fraction decreased from 28% at rest to 25% on CPS, an insignificant difference. The left ventricular shortening fraction increased in only two patients, and that increase was only 2% and 4%. In the remaining five patients the shortening fraction

Table 5-1.

	Control (cm)	CPS (cm)	p value
Left atrium	3.8 (2.9–4.4)	3.2 (2.5–3.7)	<0.04
Aortic root	3.1 (2.8–3.6)	3.3 (3.0–3.7)	NS
LVID	5.6 (4.8–6.6)	5.1 (4.6–6.2)	NS

LVID = left ventricular internal diastolic dimension.

Table 5-2.

	Control	CPS	p value
Systolic arterial pressure	127 mmHg (76–185)	87 mmHg (60–105)	<0.002
Heart rate	82 bpm (60–112)	72 bpm (51–107)	NS
Systolic pulmonary art. pressure	29 mmHg (19–49)	9 mmHg (4–19)	<0.001
Pulmonary cap. wedge pressure (mean)	13 mmHg (6–26)	1 mmHg (0–4)	<0.001

was either unchanged or diminished. In only one patient was there a significant drop in the left ventricular shortening fraction (38% to 21%); in the other four it was reduced by 3% or less.

On CPS the average systolic arterial pressure decreased from 127 mmHg (range 76–185 mmHg) to 87 mmHg (range 60–105 mmHg), $p < 0.002$ (Table 5-2). In general, the decrease in systolic pressure was proportional to the level of systolic pressure prior to initiation of CPS; the higher the control systolic pressure, the greater the pressure drop on CPS. Only one patient had an increase of systolic pressure on CPS, and he had been hypotensive prior to CPS (76 mmHg) and had an increase of 14 mmHg to 90 mmHg.

Heart rate decreased from 82 (range 60–112) to 72 (range 51–107) bpm ($p = NS$). In five patients the change in heart rate was small, <5 bpm and in one the heart rate increased 4 bpm. The slowest heart rate was 51 bpm, so bradycardia was not a factor. There was no correlation between the heart rate before and during CPS.

The average pulmonary artery systolic pressure dropped from 29 mmHg (19–49) to 9 mmHg (range 4–19 mmHg) and pulmonary capillary wedge pressure from 13 mmHg (range 6–26) to 1 mmHg (range 0–4). Both of these differences were highly significant, with p values of less than 0.001. Five of the patients had elevated pulmonary capillary wedge pressures prior to CPS, but their pressures dropped to 0–4 mmHg on CPS, as did those subjects who had normal pulmonary capillary wedge pressures prior to CPS.

All patients remained in a normal sinus rhythm, and no reflex tachycardia occurred, despite an average decrease in systemic arterial pressure of 40 mmHg after CPS had been started. In only one patient was there any increase in heart rate and that increase was very small, from 70 to 74 bpm.

The double product of heart rate and systolic blood pressure showed an average decrease from 10.5×10^3 to 6.3×10^3 ($p < 0.02$). This decrease in the double product reflects a decrease in the requirement for myocardial oxygen while on CPS.

Echocardiograms of the left ventricle were more difficult to obtain when the patient was on CPS, and in three patients the left ventricular images were technically unsatisfactory. However, in those patients who could be evaluated during CPS, there was no change in the two-dimensional echocardiographic appearance of the segmental wall motion abnormalities. In those patients who

were evaluated during balloon inflation of the coronary artery, there was hypokinesis of the affected segment of the left ventricle soon after the balloon inflation.

Doppler color flow examinations did not show any major consistent effect of the CPS on the mild aortic regurgitation. In two patients there was no change, in one patient it diminished, and in another patient it increased slightly. In the four patients with mitral regurgitation, there were two with mild and two more with moderate mitral regurgitation. In one case of moderate mitral regurgitation, there was borderline evidence of slight decrease in the regurgitation. The remainder were unchanged.

DISCUSSION

The reduction of left atrial size and pulmonary capillary wedge pressure immediately after the patients were placed on CPS reflects the decrease in intracardiac blood volume caused by diverting a major part of venous return away from the heart and indicates a reduction in left ventricular loading conditions. It is well known that myocardial oxygen requirements are proportional to left ventricular systolic pressure, left ventricular internal diameter, and heart rate. The term *double product* (systolic blood pressure × heart rate) combines two of these factors into a single value that is clinically useful. On CPS there was usually a reduction in heart rate and systolic blood pressure (with little change in ventricular dimension), and there was a consistent drop in the double product. It is partially because of the reduced need for myocardial oxygen that prolonged PTCA inflations have been so well tolerated on CPS. Although all of the patients had left ventricular wall motion abnormalities at rest, there was no new wall motion abnormality produced by the CPS alone, and global left ventricular function was not reduced.

In general, myocardial ischemia develops as a result of an imbalance between supply and demand for coronary blood flow. When a coronary artery becomes totally obstructed, myocardial ischemia results, but the extent of the ischemia depends on two factors: a) the magnitude of the myocardial mass that is totally dependent on blood flow throught the affected artery and b) the metabolic needs of the myocardium. The first factor has a relatively fixed value based on cardiac anatomy, but the second factor is extremely variable and depends on myocardial function. In patients having PTCA, if the metabolic needs of the myocardium can be reduced then the extent of ischemia caused by the balloon inflation can be minimized. This principle provides and explanation for the clinical observation that angina pectoris and electrocardiographic evidence of ischemia are infrequent on CPS, even though the arterial obstruction has caused temporary functional impairment of the myocardium. Previous work has shown that after myocardial ischemia begins, the sequence of complications that follows is first mechanical dysfunction of the myocardium and later electrocardiographic evidence of ischemia and symptoms of chest pain [6–10]. Lesser degrees of ischemia (less stenosis or

ACKNOWLEDGMENTS

We wish to thank Loretta A. Norton, RN and Janet Petit, RN for their excellent support in performing the echocardiograms.

REFERENCES

1. Lande AJ, Edwards L, Bloch JH, Carlson RG, Subramanian VA, Ascheim RS, Scheidt S, Fillmore S, Killip T, Lillehei CW. Clinical experience with emergency use of prolonged cardiopulmonary bypass with a membrane pump oxygenator. *Ann Thorac Surg* 1970; 10: 409–423.
2. Pennington DG, Merjavy JP, Codd JE, Swartz MT, Miller LL, Williams GA. Extracorporeal membrane oxygenation for patients with cardiogenic shock. *Circulation* 1984; 70(Suppl. I):I130–I137.
3. Phillips SJ, Ballantine B, Slonine D, Hall J, Vandehaar J, Kongtabwovac, Zeft RH, Skinner JR, Rekmo K, Gray D. Percutaneous initiation of cardiopulmonary bypass. *Ann Thorac Surg* 1983; 36:223–225.
4. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Emergency percutaneous cardiopulmonary bypass support in cardiogenic shock from acute myocardial infarction. *Am J Cardiol* 1989; 64:967–970.
5. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneuos cardiopulmonary bypass support in high-risk patients undergoing percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1989; 64:1258–1263.
6. Bishop VS, Kaspar RL, Barnes GE, Kardon MB. Left ventricular function during acute regional myocardial ischemia in the conscious dog. *J Appl Physiol* 1974; 37:785–792.
7. Hauser MM, Gangadharan V, Ramos OG, Gordon S, Timmis GC, Dudlets P. Sequence of mechanical, electrocardiographic and clinical effects of repeated coronary artery occlusion in human beings: Echocardiographic observations during coronary angioplasty. *J Am Coll Cardiol* 1985; 5:193–197.
8. Wohlgelernter D, Cleman M, Highman HA, Fetterman RC, Duncan JS, Zaret BL, Jaffe CC. Regional myocardial dysfunction during coronary angioplasty: Evaluation by two-dimensional echocardiography and 12-lead electrocardiography. *J Am Coll Cardiol* 1986; 7:1245–1254.
9. Chierchia S, Brunelli C, Simonetti I, Lazzari M, Maseri A. Sequence of events in angina at rest: Primary reduction in coronary flow. *Circulation* 1980; 64:759–67.
10. Chierchia S, Lazzari M, Freeman B, Brunelli C, Maseri A. Impairment of myocardial perfusion and function during painless myocardial ischemia. *J Am Coll Cardiol* 1983; 924–930.
11. Bertrand ME, Lablanche JM, Fourrier JL, Traisnel G, Mirsky I. Left ventricular systolic and diastolic function during acute coronary artery balloon occlusions in humans. *J Am Coll Cardiol* 1988; 12:341–347.

6. PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT: TECHNIQUE, INDICATIONS, AND COMPLICATIONS

FAYAZ A. SHAWL

INTRODUCTION

Atherosclerotic cardiovascular disease remains the most common cause of death in the United States and other industrialized countries. The first major advance in the treatment of atherosclerosis was coronary artery bypass graft surgery. The subsequent introduction of percutaneous transluminal coronary angioplasty (PTCA) began a new era of treatment of cardiovascular disease.

The growth of PTCA, as well as the complexity of approachable lesions, has continued to increase since its introduction by Dr. Andreas Greuntzig in 1977 [1]. PTCA was initially limited to patients with single-vessel coronary artery disease and normal left ventricular function [2]. However, with advances in catheter technology, including guiding catheter development and increased operator experience, the application of PTCA has been extended to patients with multivessel coronary disease, unstable angina, acute myocardial infarction, and symptomatic patients with prior coronary bypass graft surgery [3–5].

Despite such a dramatic increase in the number of PTCAs, there remain certain limitations, such as abrupt closure, which occurs in approximately 5% of cases [6,7]. While most patients tolerate abrupt closure, it is nonetheless associated with a mortality rate between 2% and 12%, as well as a Q-wave myocardial infarction rate of more than 25% when such patients are sent for emergency coronary bypass graft surgery [8,9]. Some patients, particularly those with poor left ventricular function, may experience hemodynamic

collapse following abrupt closure, and these patients may not even tolerate transient ischemia during balloon dilatation.

The cardiac catheterization laboratory has been transformed from a purely diagnostic to an interventional setting. Coronary intervention is being undertaken in increasingly high risk patients, and therefore, there is a clear need to provide effective, temporary circulatory support.

Recently [10], femero-femoral cardiopulmonary bypass support has been introduced to provide hemodynamic support to certain high risk patients undergoing PTCA, but the necessity for surgical cutdown has limited its use in the catheterizaiton laboratory, particularly in emergencies.

The author [11,12] has recently developed a percutaneous technique for establishing femoro-femoral cardiopulmonary bypass support in awake, conscious patients in the catheterization laboratory. This report describes the technique, suggested indications, patient management while on cardiopulmonary bypass support, as well as complications encountered during percutaneously established cardiopulmonary support at our institution.

SUGGESTED INDICATIONS

In the past, cardiopulmonary bypass support using the femoral approach, has been used predominantly in emergency situtations outside the cardiac catheterization laboratory. Lande et al. [13] instituted cardiopulmonary bypass support in the emergency room in 18 patients with either cardiogenic shock, cardiac arrest, or pulmonary insufficiency. The duration of cardiopulmonary bypass support varied from 45 minutes to 2 hours, with 16 patients showing marked improvement. They reported that three patients were long-term survivors. Subsequently, Baird and his colleagues [14] treated 25 patients in cardiac arrest with cardiopulmonary bypass support. Twenty-eight of these otherwise terminally ill patients survived using the femoral approach. Also, Mattox and Beall [15] described the application of portable cardiopulmonary bypass support in 43 patients who were *in extremis*. There were 17 long-term survivors (up to 10 years). However, it was not until 1982 that Phillips [16] and his coworkers decribed the percutaneous initiation of cardiopulmonary bypass support in five patients with refractory cardiac arrest. They used 12 Fr cannulae and achieved a flow rate of only 2–2.5 l/min.

The application of a portable cardiopulmonary bypass support system in the setting of coronary angioplasty was first reported by Kanter and his coworkers [17], who used it to revive six patients with cardiac arrest or cardiogenic shock as a result of complications due to coronary angioplasty. These patients were unresponsive to conventional resuscitation, including intraaortic balloon pumping. Subsequently, Vogel et al. [10] described three patients in whom coronary angioplasty was performed using prophylactic cardiopulmonary bypass support. In these three patients, and in Kanter's group [17], cardiopulmonary bypass support was instituted using 18 or 20 Fr bypass cannulae placed by surgical cutdown.

Table 6-1. Suggested current and future indications for percutaneous cardiopulmonary bypass support

Abrupt vessel closure associated with hemodynamic collapse
Cardiac arrest in the catheterization laboratory
High risk coronary angioplasty
High risk valvuloplasty
Cardiogenic shock caused by acute myocardial infarction
Massive pulmonary embolism prior to pulmonary embolectomy
Prevention of reperfusion injury with the use of cardioplegic solution
During electrophysiologic testing — Compromising ventricular tachycardia
Hypothermia
Thoracic aneurysm
Prior to repeat coronary bypass surgery
Near drowning
Drug Overdose
Bridge to other mechanical assist devices or cardiac transplant

In 1988 the author [11] introduced the technique of percutaneous cardiopulmonary bypass support (PCPS) using 18 or 20 Fr cannulae in patients undergoing emergency, as well as elective high risk interventions.

The basic indications for the institution of percutaneous cardiopulmonary bypass support can be categorized as either elective or emergent [18–23]. PCPS may be instituted electively as a prophylactic measure during high risk coronary angioplasty (supported angioplasty), which is discussed in detail in Chapter 7. Patients considered for emergent PCPS include those in cardiogenic shock from acute myocardial infarction. The use of PCPS in cardiogenic shock is discussed in Chapter 8. PCPS has also been used to support patients who sustain cardiac arrest in the catheterization laboratory (see Chapter 9). Other suggested indications for the institution of PCPS are shown in Table 6-1.

CONTRAINDICATIONS

PCPS requires the use of an intense anticoagulation regimen, making the procedure inappropriate in patients with contraindications to anticoagulation. The other important contraindication is severe peripheral vascular disease. In certain selected patients, iliofemoral angioplasty has been performed prior to the insertion of the bypass cannula. The contraindications are summarized in Table 6-2.

TECHNIQUE OF ELECTIVE PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT (PCPS)

Patients are prepared and draped in the catheterization laboratory, in the usual sterile manner, exposing both groins. All items necessary for the percutaneous cannulae insertion (Figures 6-1 and 6-2; see color plates p. 79) are available in a compact kit (Percutaneous Insertion Kit, Shawl™ Technique, C.R. Bard, Inc., Billerica, MA).

Table 6-2. Contraindication to the institution of percutaneous cardiopulmonary bypass support

Severe peripheral atherosclerotic disease
History of recent cerebral vascular accident
Preexisting coagulopathy
Active bleeding
Untreatable or terminal disease
Suspected traumatic closed head injury
Unwitnessed normothermic cardiac arrest
Refractory cardiac arrest of long duration (normothermic)
Severe aortic regurgitation

Iliofemoral angiography

Using the Seldinger technique, a 7 Fr pigtail catheter is introduced into the right femoral artery in order to preform iliofemoral angiography, initially visualizing the left side (Figure 6-3) and then, if necessary, the right side. The tip of the pigtail is positioned just above the bifurcation of the aorta and 20 cc of a contrast agent is power injected at a rate of 10 cc/sec. Prior to angiography, a needle (the same as used for percutaneous vascular access) is placed along the groin crease as a marker in order to establish the relationship of the skin crease to the bifurcation of the femoral system, and as a guide for arterial entry (Figure 6-3B). If the left iliofemoral system (Figures 6-4 and 6-5) indicates a suitable anatomy, a Swan Ganz catheter is placed in the right femoral vein and advanced to the pulmonary artery for the monitoring of hemodynamic parameters prior to, during, and after the procedure. If the anatomy of the left iliofemoral system is unsuitable (small caliber or critically diseased) for bypass cannulae, angiography is performed on the right side using the same technique. If the left iliofemoral system reveals acceptable anatomy for the insertion of a bypass cannula, the pigtail catheter is exchanged over a standard 0.038 in. guidewire for a standard 8 Fr long angioplasty sheath (U.S.C.I. Division, C.R. Bard, Billerica, MA), which is introduced in the right femoral artery.

Cannulation

Access to the left femoral artery and vein is obtained using a standard single-wall needle, and 7 or 8 Fr sheaths are left in place. With knowledge of the iliofemoral anatomy, together with its relationship to the skin crease (needle marker), the common femoral artery (Figure 6-5), or the femoral artery below the bifurcation (if of adequate caliber), is entered (Figures 6-3 and 6-4). Care is taken to ensure that the actual arterial puncture site is below the inguinal ligament (the line joining the iliac crest and symphysis pubis) in order to facilitate subsequent external clamp placement for hemostasis. Patients are then heparinized with 225 U heparin (as a single bolus) per kilogram of body weight to obtain an activated clotting time of $\geq$400 seconds, which is checked

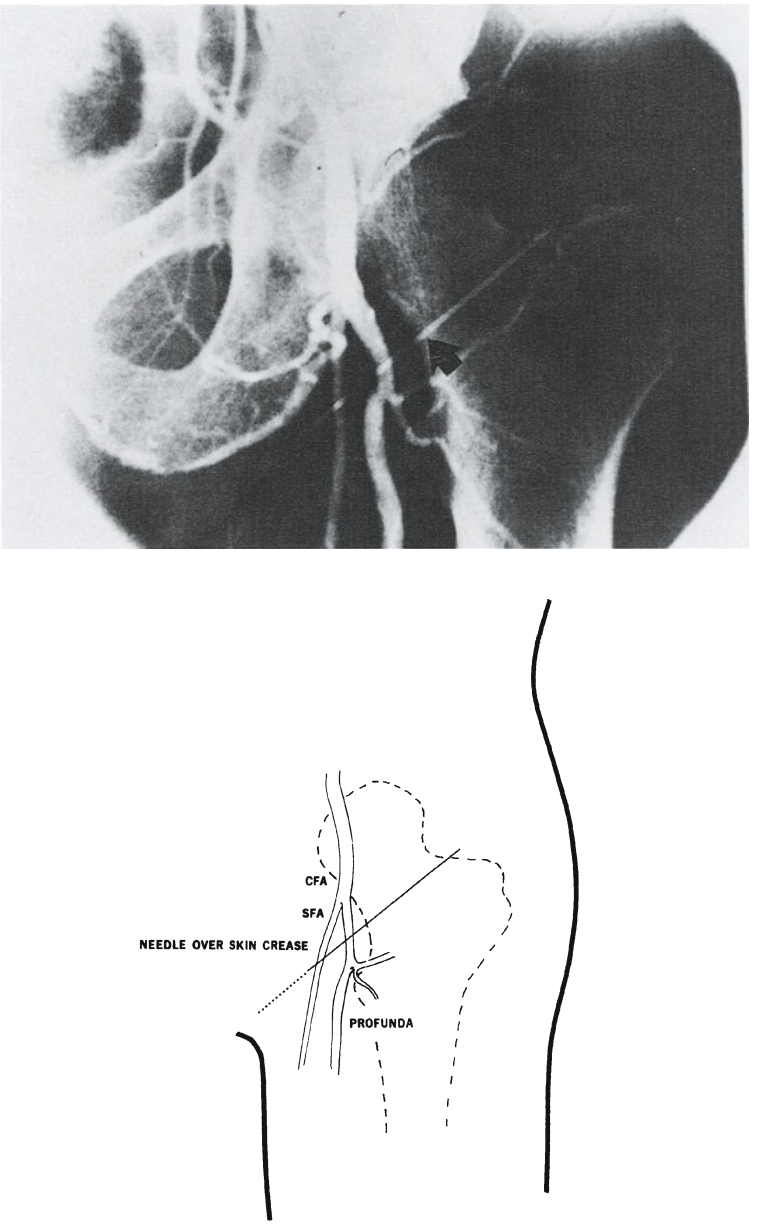

Figure 6-3. *A*: left iliofemoral cineangiogram performed prior to cannulation to assess adequacy for cannula placement. The skin crease is marked with a radioopaque needle (arrow) placed on the surface of the skin before angiography. *B*: Schematic representation of the iliofemoral system with needle marker in place. Note that the angiogram allows selection of the appropriate vessel for cannulation (profunda rather than SFA or CFA in the case). CFA = common femoral artery; SFA = superficial artery.

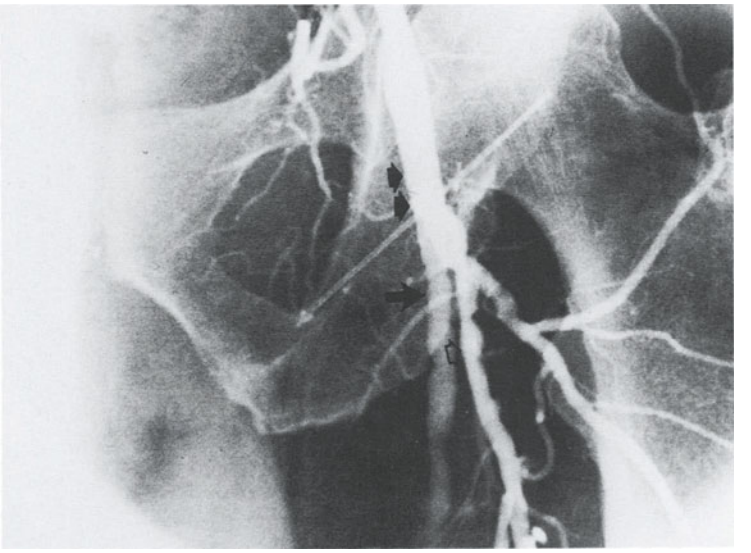

Figure 6-4. Left iliofemoral cineangiogram with needle maker left in place. Note that the appropriate vessel for cannulation is the SFA (arrow) or common femoral (double arrows) rather than profunda (open arrow). SFA = superficial femoral artery.

after 10 or 15 minutes. The percutaneous insertion kit, which also contains the 18 Fr cannulae, is next opened. Then, the 0.038 in. flexible guidewire is introduced through the arterial sheath (the arterial bypass cannula is introduced before the venous cannula). Keeping this 0.038 in. flexible guidewire in place, the arterial sheath is removed and a long 8 Fr dilator is introduced. The tip of this long dilator usually lies above the bifurcation of the descending aorta. The 0.038 in. flexible guidewire is removed and replaced with the stiff 0.038 in. guidewire with a flexible tip. Holding the stiff guidewire in place (its soft tip should remain above the level of the diaphram), the long 8 Fr dilator is removed, and the vessel is then dilated with a 12 Fr and then a 14 Fr dilator. Before the 14 Fr dilator is removed, a 1–2 mm skin incision is made at the entry site using #11 blade to accomodate the bypass cannulae. The 14 Fr dilator is removed, and an 18 Fr arterial cannula (C.R. Bard, Inc.) is advanced over the stiff guidewire using a rotary motion, taking care to advance both dilator and cannula assembly as a single unit so that the cannula does not buckle. This is best accomplished by having an assistant hold the proximal end of the cannula-dilator unit firmly together. After the introduction of the 18 Fr arterial cannula (in our initial series 20 Fr cannulae were used), the guidewire

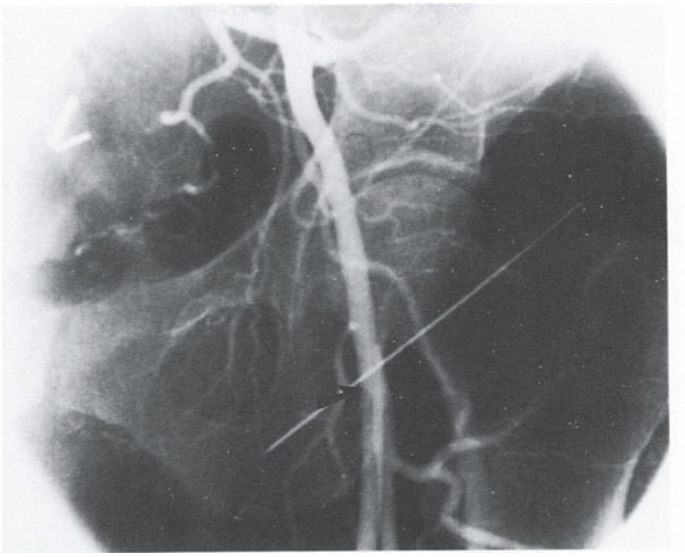

Figure 6-5. Left iliofemoral cineangiogram showing a low bifurication of the common femoral artery. Here, the appropriate vessel for cannulation is the common femoral (arrow). CFA = common femoral artery.

and the dilator are removed and the tubing is closed quickly using the available Robert's clamp (Figure 6-6; see color plates p. 80). Employing a similar approach, an 18 Fr multihole venous cannula (C.R. Bard, Inc.) is advanced until the tip is positioned just above the junction of the inferior vena cava and the right atrium (Figure 6-6). During advancement of the venous cannula, the soft tip of the stiff guidewire is positioned in the superior vena cava.

Iliofemoral angiography is not performed in patients who present with cardiac arrest in the catheterization laboratory. Bypass cannulae are placed in these patients using previous arterial and venous access sites or using bypass cannulae from the right femoral approach. After the patient has been placed on cardiopulmonary bypass support, the contralateral femoral vessel is used for angiography or intervention if indicated. In patients with cardiogenic shock, diagnostic angiography is performed after bypass support is initiated.

It takes less than 4 minutes to cannulate a patient for PCPS using the author's technique after venous and arterial access is obtained. While cannulation is being performed, a perfusionist primes the disposable perfusion circuit (C.R. Bard, Inc.).

ADDITIONAL TECHNICAL CONSIDERATIONS

Tortuous iliofemoral arterial system

A tortuous, but patent, iliofemoral system does not preclude cannula placement if the vessels are of adequate size (Figure 6-7). In approaching a tortuous system, it is important to first pass a very flexible guidewire into the descending aorta. A long dilator (see Figure 6-1) is then advanced over the flexible guidewire, and the flexible guidewire is exchanged for a stiff guidewire via the long dilator. The long dilator is then removed over the stiff guidewire, leaving the tip of the stiff guidewire above the level of the diaphram. The stiff guidewire straightens the artery (Figure 6-7D), allowing safe placement of the arterial cannula (Figure 6-7E). If the contralateral vessel is of adequate size and is less tortuous, it may be used instead.

Critical iliofemoral stenoses

Severe iliofemoral disease should prompt arteriography of the contralateral system. If both systems are severely diseased, then angioplasty of the iliofemoral system may be performed if feasibile, followed by immediate cannula placement (Figure 6-8). Iliofemoral disease sufficiently severe to require angioplasty prior to cannula placement has been infrequent due to an attempt to exclude patients with symptoms suggestive of peripheral vascular disease.

Abdominal aortic aneurysm

Although our experience has been limited (four cases), the presence of an abdominal aortic aneurysm (Figure 6-9) does not appear to preclude cannula placement, because the tip of the arterial cannula is generally at or below the aortic bifurcation.

PORTABLE CARDIOPULMONARY SUPPORT SYSTEM

The cardiopulmonary bypass support system (CPS™ C.R. Bard, Inc.) is a battery-operated portable system on a hospital cart (Figure 6-10; see color plates p. 80) with a disposable CPS circuit (Figure 6-11) that includes a centrifugal, nonocclusive pump (Bio-Pump), a polypropylene hollow fiber membrane oxygenator, clamps, connectors, and a heat exchanger. The perfusion circuit is primed by a perfusionist using 1300 cc of Normosol (Abbot Laboratories, Abbot Park, IL). It takes less than 10 minutes to set up and prime this system. The details regarding system operation and priming of the perfusion circuit is described in Chapters 3 and 10.

Figure 6-7. *A,B*: Cineangiogram prior to cannula placement showing severe tortuosity of the left iliofemoral system. *C*: Flexible guidewire in place in the left iliofemoral system. The J-tip should be positioned above the level of the diaphram (not shown here). Passage of the wire is facilitated by advancing the long dilator. *D*: The stiff guidewire in place (note straightening of the tortuous artery by the stiff guidewire). *E*: Arterial bypass cannula in place (note the continued straightening of the initially tortuous vessel).

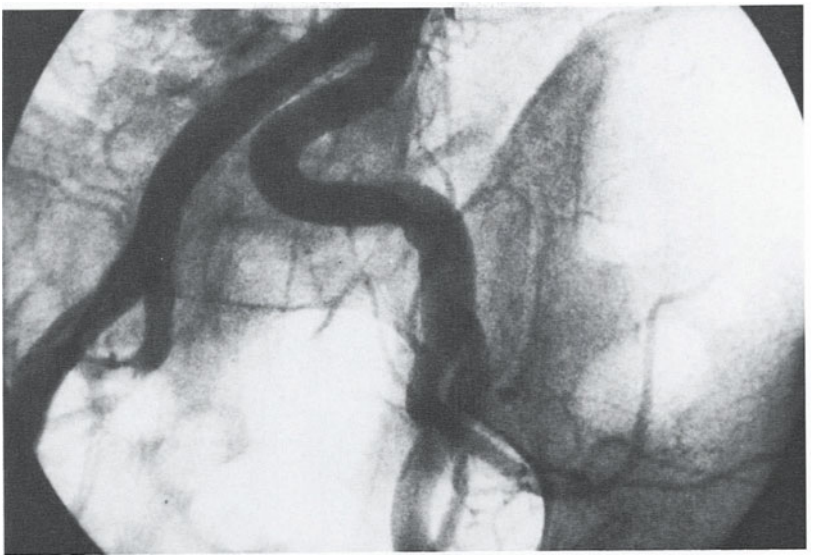

Figure 6-7A

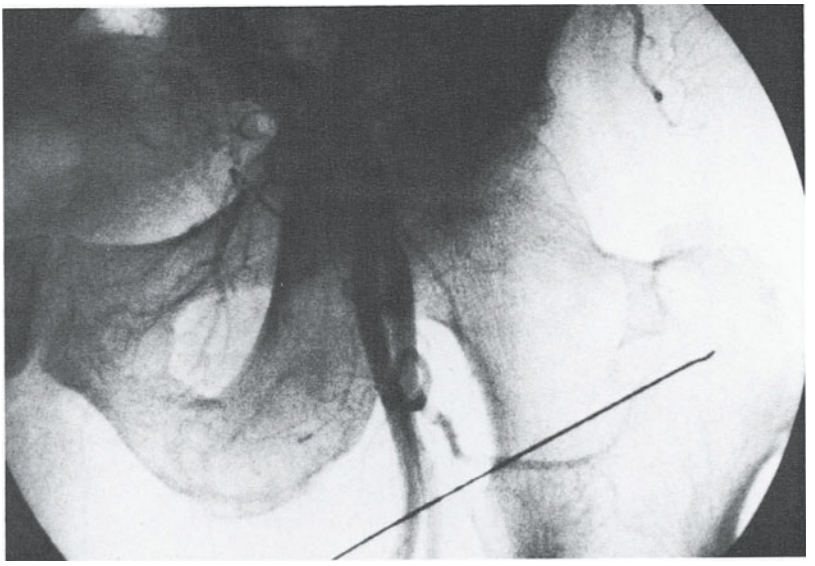

Figure 6-7B

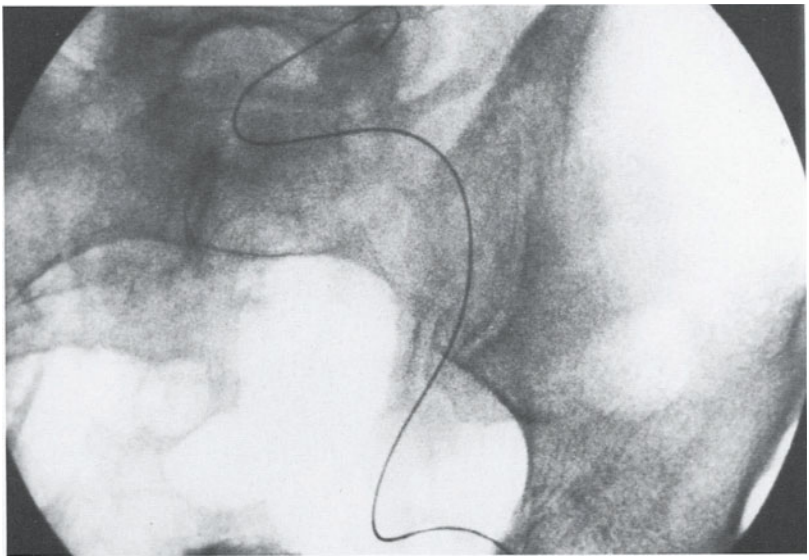

Figure 6-7C

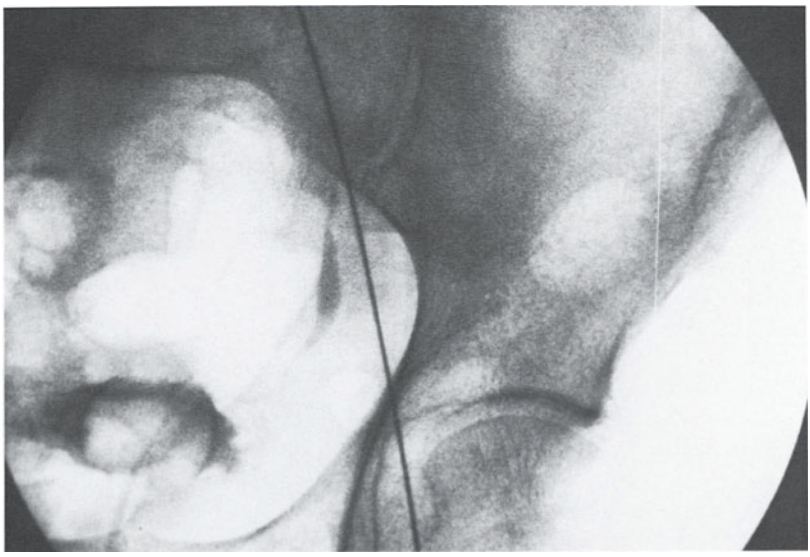

Figure 6-7D

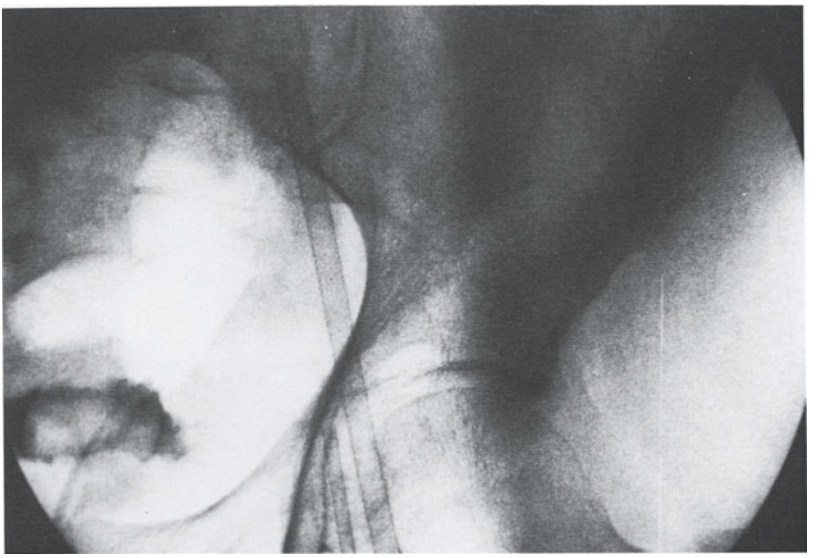

Figure 6-7E

INITIATION OF CARDIOPULMONARY BYPASS SUPPORT

Baseline hemodynamic measurements, which include arterial, pulmonary artery, and pulmonary capillary wedge pressures, are obtained prior to the insertion of bypass cannulae. The arterial cannula is backbled by opening the Robert's clamp prior to its connection to the primed perfusion circuit. Next, venous and arterial cannulae are attached to the CPS perfusion circuit, making sure that there are no air bubbles, particularly on the arterial side. Before the initiation of any flow, it is important to keep venous lines closed to the atmosphere. Elective patients are kept well hydrated before the initiation of cardiopulmonary bypass support. If pulmonary artery diastolic (or pulmonary capillary wedge) pressure is <8 mmHg, rapid volume infusion through the pump is given prior to full institution of bypass flow.

During elective supported angioplasty, cardiopulmonary bypass support is started using 2 l of flow per minute (Figure 6-12) with increments of 0.5 l/min if pulmonary artery diastolic pressure (or pulmonary capillary wedge) is >5 mmHg (Figures 6-12B and 6-13) or >50% of the baseline or chest pain or electrocardiographic changes occur with an increase in the filling pressure after less than 2 minutes of balloon inflation (Figures 6-12C to 6-12E).

At times, a "chattering" of the venous line occurs during an attempt to increase the flow rate with a reduction in blood flow, as reflected on the blood flow meter. This is an indication of intermittent collapse of the vena cava

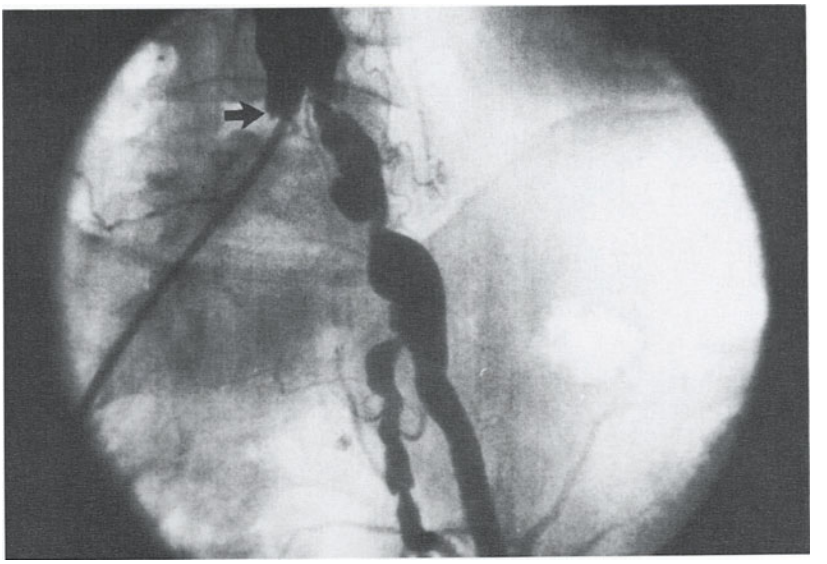

Figure 6-8A

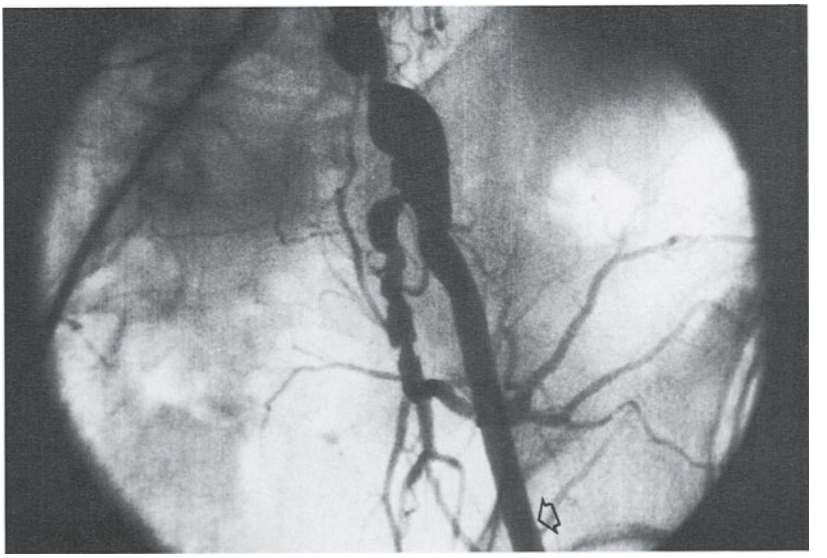

Figure 6-8B

Figure 6-8. *A,B*: Cineangiogram prior to cannula placement showing a totally occluded right common iliac (arrow) and critical stenoses involving the left iliac system but disease-free common femoral (open arrow).

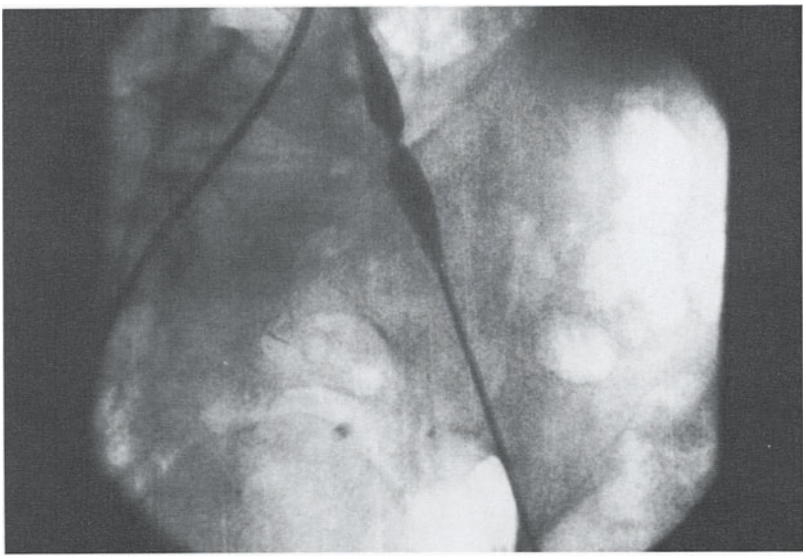

Figure 6-8C

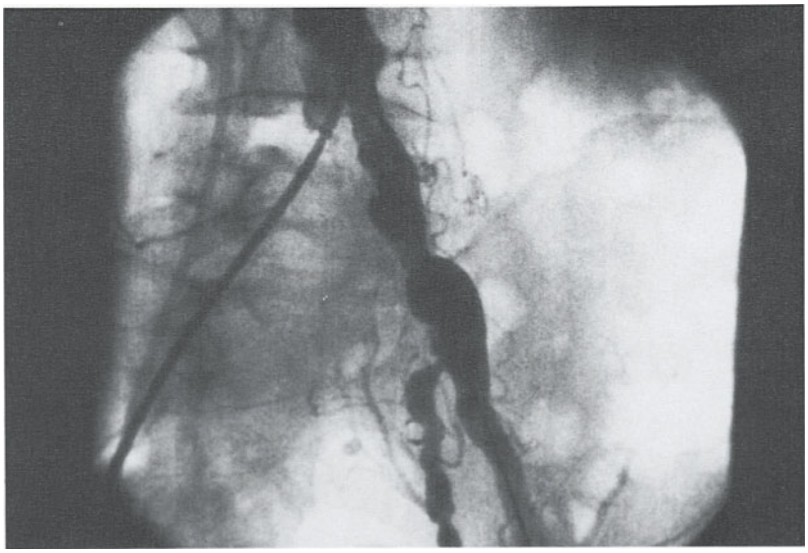

Figure 6-8D

Figure 6-8. *C*: Peripheral angioplasty of the left iliac stenosis prior to cannulation. *D*: Post-angioplasty result in left iliac.

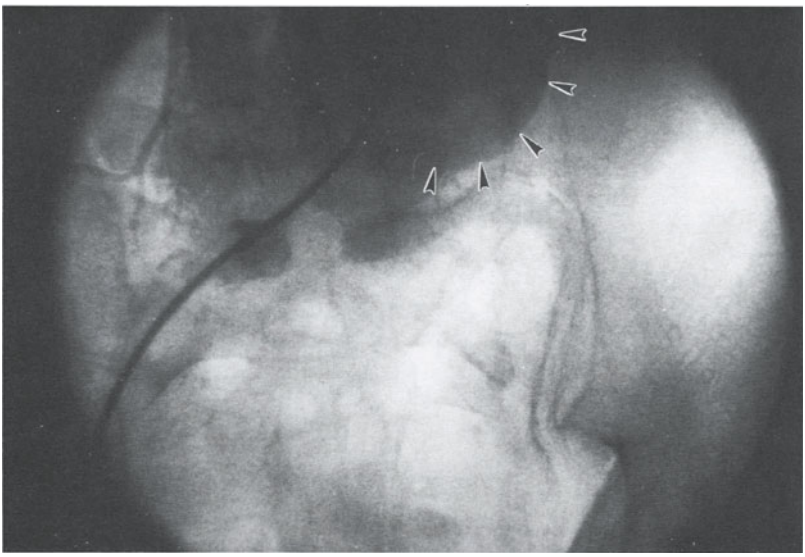

Figure 6-9. Cineangiogram of a large abdominal aortic aneurysm (arrows) that terminated above the bifurcation of the aorta (the bifurcation is not shown). In this case, bypass cannulae were placed via the left femoral system without complication.

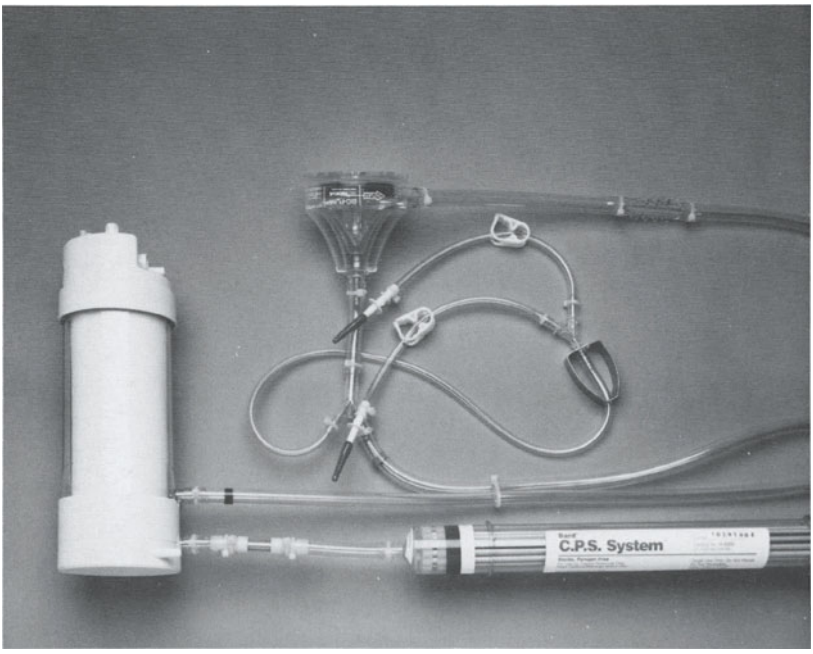

Figure 6-11. Disposable cardiopulmonary bypass circuit, which includes the membrane oxygenator, nonocclusive pump, heat exchanges, and tubing.

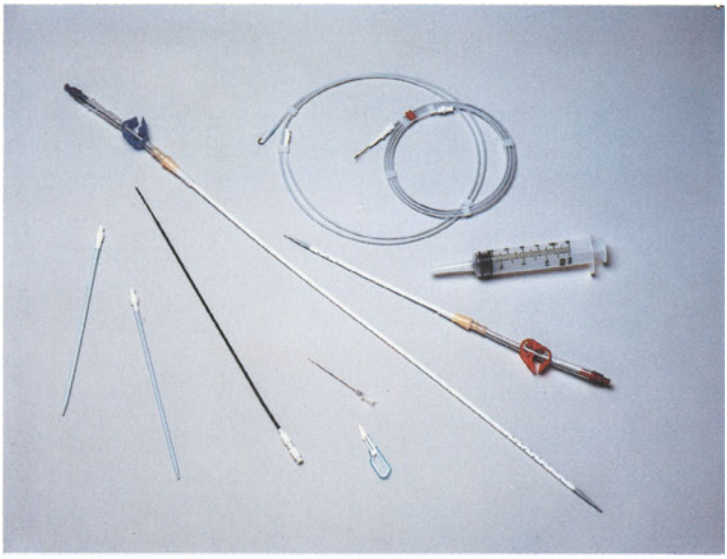

Figure 6-1. Equipment necessary for percutaneous cannula insertion, including 18 Fr arterial and venous cannulae, dilators, guidewires, syringe, needle, and scalpel blade.

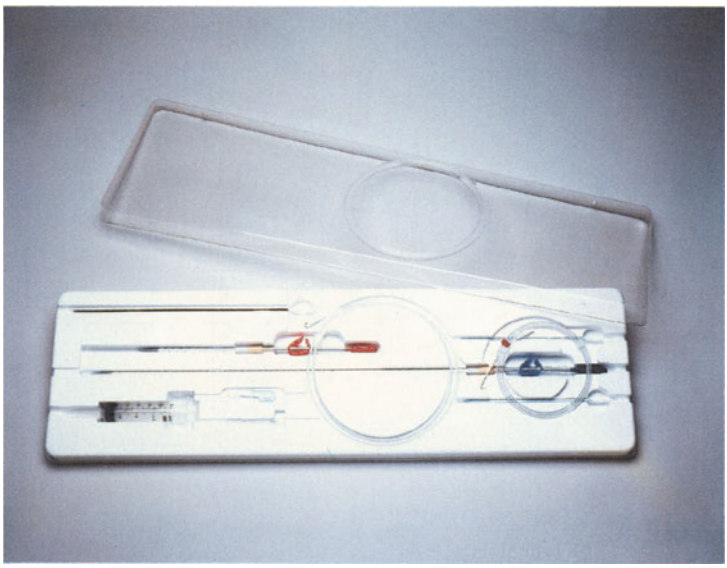

Figure 6-2. Commercially available kit (C.R. Bard, Billerica, MA) containing all components necessary for percutaneous cannula insertion in a single, sterile package.

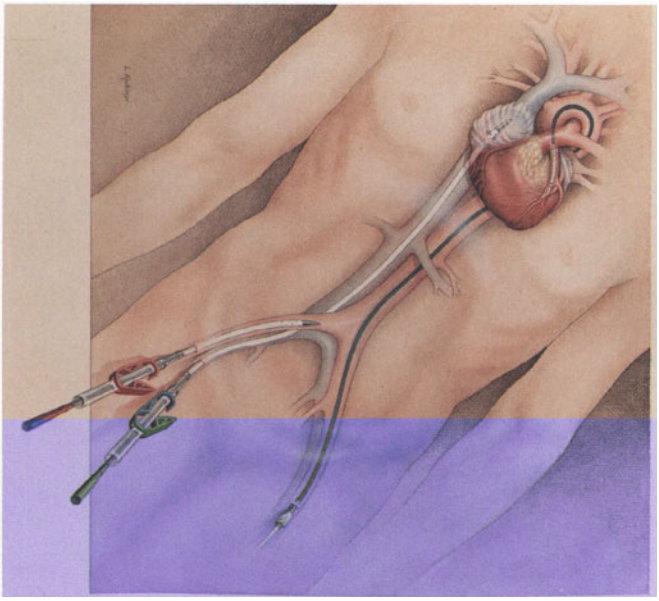

Figure 6-6. Schematic representation of the appropriate position of the arterial and venous cannulae. Note placement of the tip of the venous cannula just above the junction of the inferior vena cava and right atrium. The arterial cannula is advanced until the hub is flush with the skin. Also note that a right femoral approach is shown in the diagram, whereas the left femoral approach is more commonly used in elective cases with PTCA performed from the contralateral side.

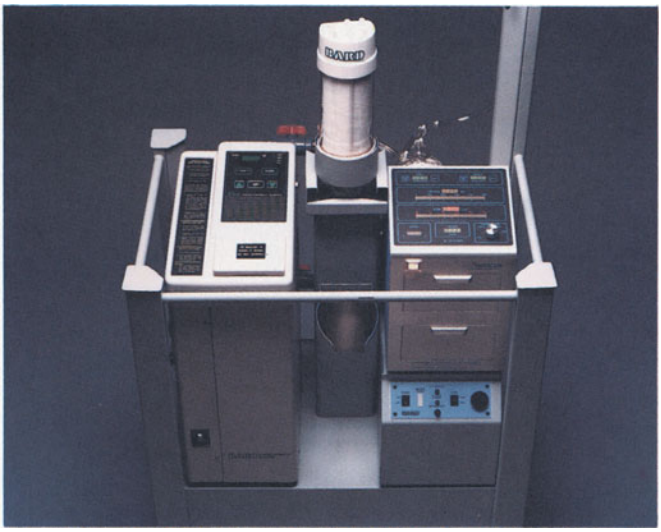

Figure 6-10. Portable cardiopulmonary bypass support system.

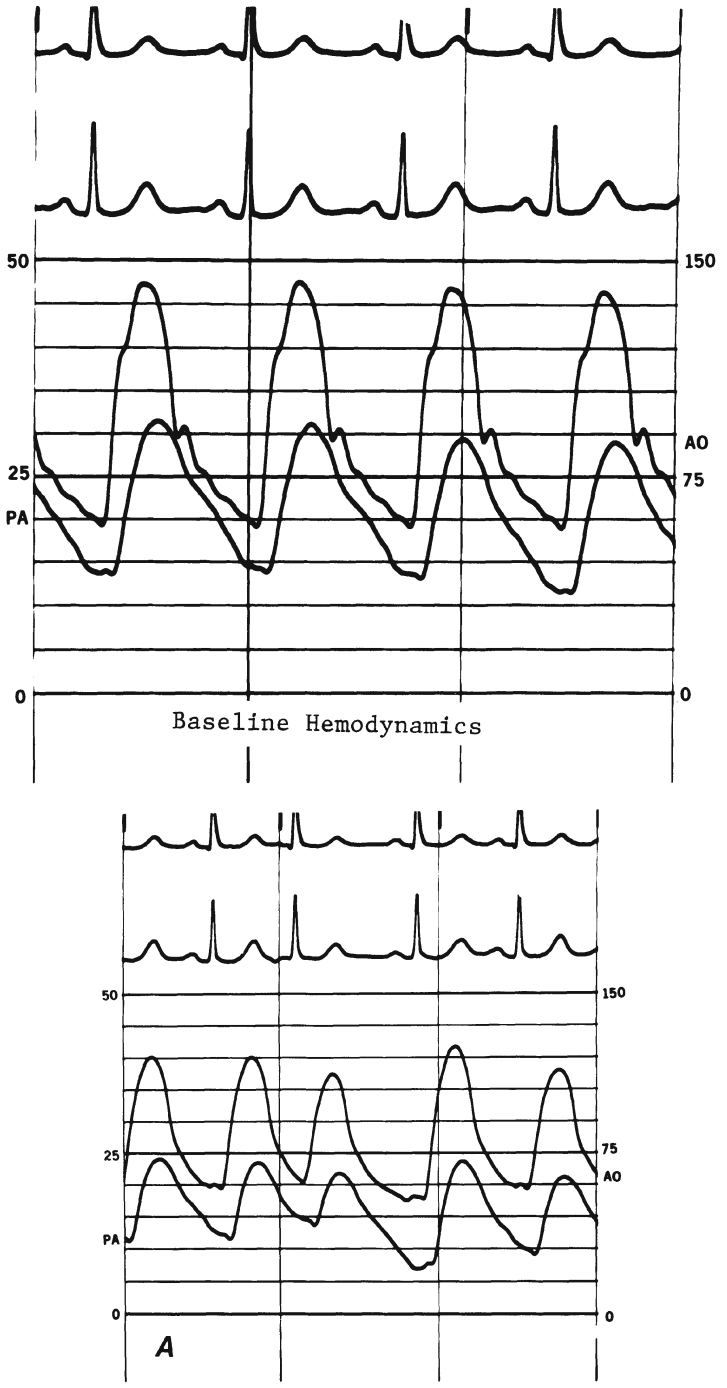
50
150
AO
25
75
PA
0
0
Baseline Hemodynamics
50
150
25
75
AO
PA
0
0
A

Figure 6-12A

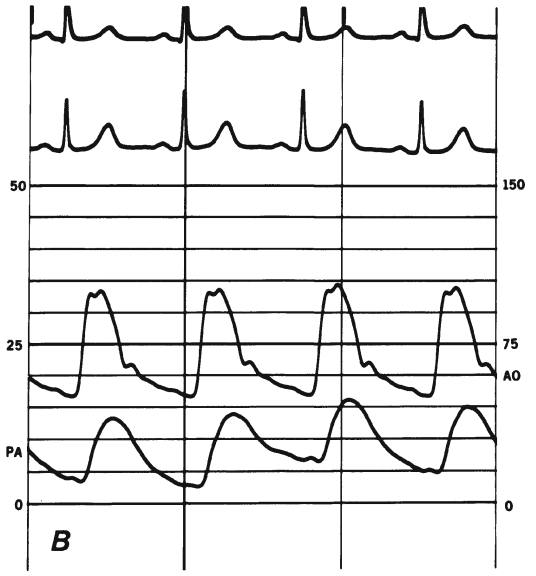

Figure 6-12B

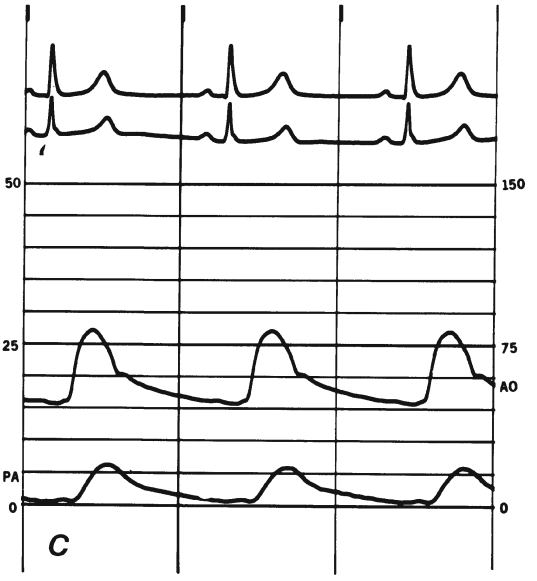

Figure 6-12C

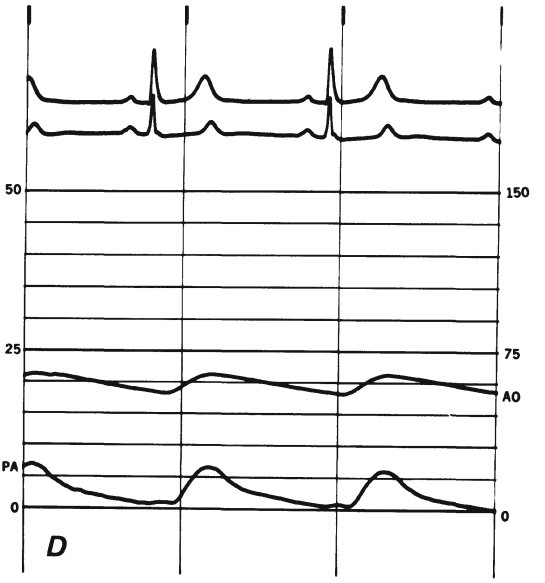

Figure 6-12D

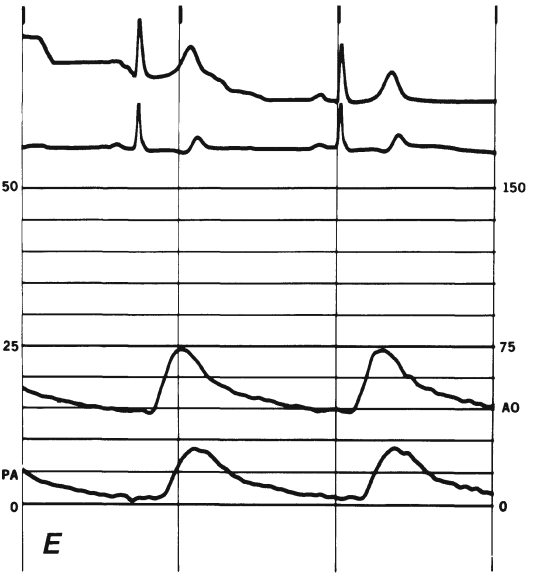

Figure 6-12. [Case example of a patient undergoing elective supported PTCA with a baseline BP of 140/60 mmHg and a PA pressure of 30/14 mmHg]. Aortic and PA pressures at A, 2 l/min of bypass flow; B, 2.5 l/min bypass flow. *C*: Further reduction in AO and PA pressures present 5 minutes after increasing the flow to 2.5 l/min (Note minimal change in the diastolic BP). *D*: During balloon inflation there is no increase in the PA diastolic pressure. Note reduced pulse pressure in the AO pressure tracing secondary to reduced left ventricular ejection. *E*: Return of left ventricular ejection demonstrated by increase in AO pulse pressure. AO = aortic; BP = blood pressure; PA = pulmonary artery; PCW = pulmonary capillary wedge.

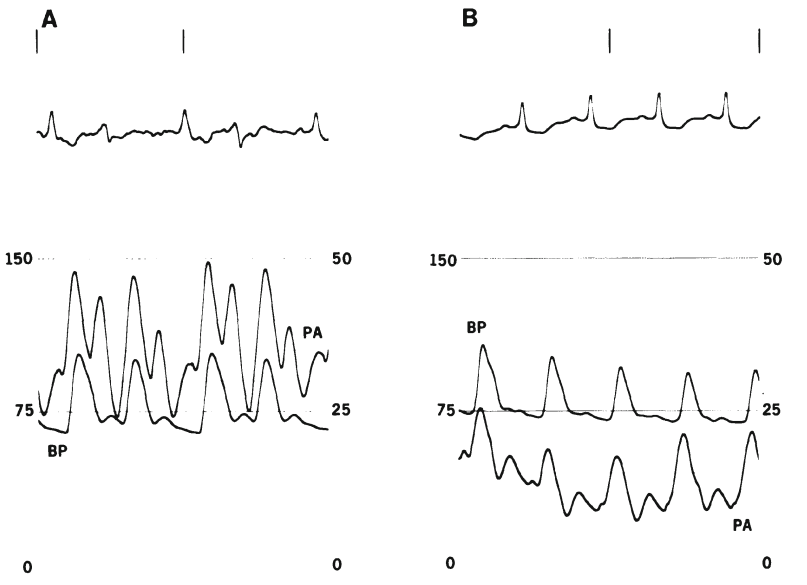

Figure 6-13. Example of a patient undergoing elective, supported PTCA requiring 3.5 l/min flow to reduce the PA diastolic pressure to <50% (B) of baseline (A).

around the venous cannula, which can be resolved by reducing the speed of the blood pump, adding volume, and then increasing pump speed until a corresponding increase of blood flow cannot be demonstrated.

Significant hypotension, defined as a mean pressure of <60 mmHg (a lower blood pressure can be tolerated if the patient is awake and responding to verbal commands), can be corrected in most patients by volume infusion through the pump (Figure 6-14). In certain circumstances, particularly if the systemic vascular resistance is low, neosynephrine infusion may be necessary.

In patients in cardiogenic shock or cardiac arrest, an estimate of the blood flow requirement can be calculated based upon the patient's body surface area or body weight (2.2–2.4 l/m^2 or 50–60 ml/kg body weight).

Activated clotting time is measured every 15 minutes and is maintained at or above 400 seconds. Arterial blood gas, mixed venous oxygen saturation, and electrolytes are determined periodically in all patients. All patients who have sustained cardiac arrest are intubated.

PTCA TECHNIQUE IN ELECTIVE GROUP

The patients who undergo elective supported angioplasty are premedicated with aspirin, 325 mg daily, prior to the procedure, when this is feasible. An infusion of low molecular weight Dextran is started 3–4 hours prior to the

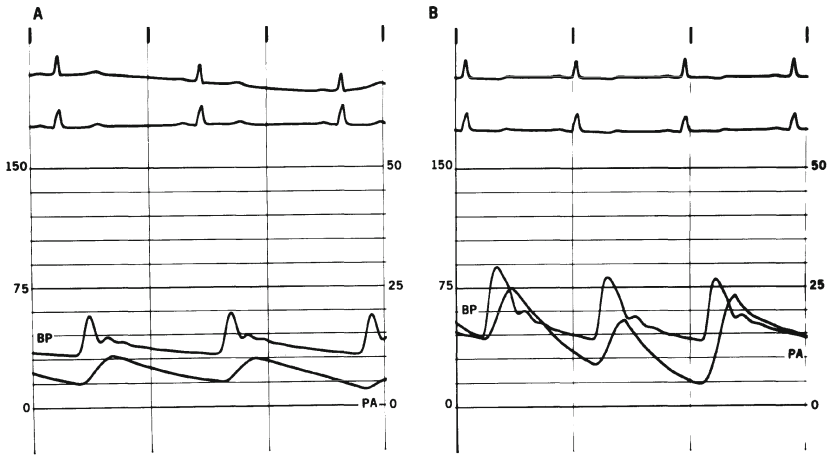

Figure 6-14. Elevation of systemic BP on bypass in reponse to volume infusion (B). This is the expected reponse when the filling pressure is low (A).

procedure at a rate of 50 ml/min, unless the patient is in congestive cardiac failure. PTCA is then performed from the contralateral femoral artery in the standard fashion after the establishment of cardiopulmonary bypass support. PTCA of the culprit vessel (based upon vessel size and the amount of myocardium in jeopardy) is initially performed and, if successful, additional vessels are also attempted. If patients are receiving intravenous nitroglycerin or heparin prior to PTCA (e.g., in unstable angina), both are continued. The heparin infusion is discontinued after the standard bolus of heparin at the time of cannulation for PCPS.

SUBSEQUENT THERAPY IN CARDIOGENIC SHOCK AND CARDIAC ARREST

In patients in cardiogenic shock, left ventriculography and coronary angiography are performed after hemodynamic stability is achieved. If feasible, the infarct related vessel is dilated. Other critically narrowed vessels are also dilated if a good result is obtained in the infarct vessel and the lesion characteristics (low risk) in the noninfarct vessel(s) appear amenable to PTCA. If the patient's coronary anatomy is not favorable for PTCA, emergency coronary bypass surgery is undertaken, with the patient being transported to the operating room while still on PCPS.

Patients in cardiac arrest with ventricular fibrillation are defibrillated (Figure 6-15). Patients who are initally asystolic usually return to sinus or junctional rhythm within a few minutes following institution of bypass, and pacemaker insertion is rarely necessary.

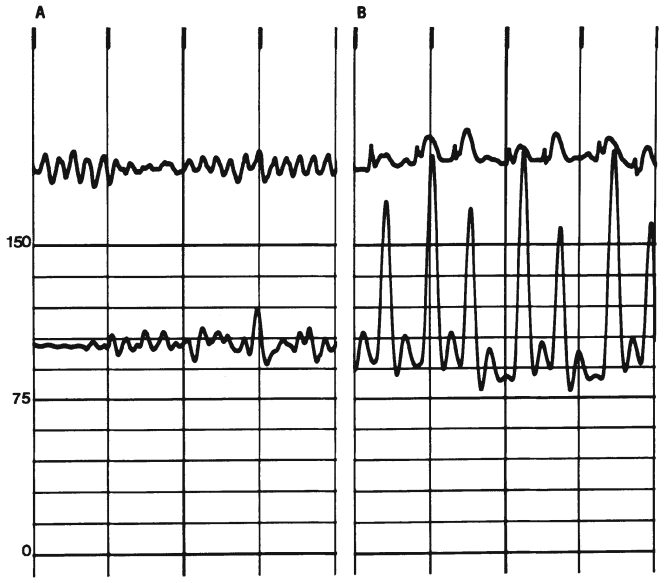

Figure 6-15. A 64-year-old woman with a chronic total occlusion of the left anterior descending coronary artery sustained a cardiac arrest post-PTCA (due to acute closure of the right coronary artery). She was unresponsive to cardiopulmonary resuscitation. *A*: Mean blood pressure of 104 mmHg after institution of bypass at a flow rate of 5 l/min while in ventricular fibrillation. *B*: After defibrillation, the patient is in normal sinus rhythm (intravenous diazepam was given before defibrillation because the patient was awake).

Patients who are not candidates for revascularization are gradually weaned from bypass over the next few hours.

Patients who undergo emergency bypass graft surgery are transported to the operating room on PCPS, which is terminated after standard cardiopulmonary bypass support (right atrium to aorta) is established. In order to avoid air embolism, care should be taken to be certain that PCPS is terminated before atrial cannulation for standard cardiopulmonary bypass. Also, no venous entry should be attempted while the patient is still on PCPS.

TERMINATION OF CARDIOPULMONARY BYPASS SUPPORT (ELECTIVE GROUP)

Following the completion of successful PTCA in the elective group, cardiopulmonary bypass support is weaned over 3–5 minutes by gradually reducing the bypass flow rate. Generally, the bypass flow is reduced by about 0.5 l/every minute. Volume is infused as necessary to increase the left ventricular filling pressure (estimated by the pulmonary capillary wedge or pulmonary

artery diastolic pressure) to at least 8–10 mmHg or to the prebypass level (whichever is less).

In some patients, particularly those with severe left ventricular dysfunction or recent myocardial infarction, inotropic agents (dopamine or dobutamine) may be necessary in order to wean the patient from bypass. Rarely an intra-aortic balloon pump is necessary, which is placed via the contralateral femoral artery.

The patient is then transferred to the coronary care unit on a stretcher. Weaning and subsequent termination of PCPS can be done in the coronary care unit if the patient is not weaned in the catheterization laboratory within about 30 minutes, which happens very rarely. The stretcher commonly used consists of a flat metal surface with an adjustable head support (Haustead, Medina, Ohio). A mattress with an egg crate supplement and a pillow with the head elevated approximatley 15° is used for patient comfort.

A cell saver is used to autotransfuse the blood remaining in the bypass perfusion circuit. After autotransfusion is completed, the activated clotting time is checked in the coronary care unit.

REMOVAL OF BYPASS CANNULAE (ELECTIVE GROUP)

Bypass cannulae are removed when the activated clotting time falls below 240 seconds. It takes 5–8 hours after the last dose of heparin to achieve this level of activated clotting time. After the cannulae are removed, manual compression for hemostasis is performed for 15–20 minutes (Table 6-3). During this period of manual compression, an assessment of the appropriate point for clamp compression is made. Also, after 15 or 20 minutes of local compression, the pressure is slightly relaxed (without allowing bleeding) in order to assess the status of the pedal pulse. This allows an estimate of the degree of clamp pressure necessary for subsequent clamp compression.

Then a new, modified disc (Comfort Disc, Instromedix, Hillsboro, OR) along with a locked compression clamp (Compressar, Instromedix, Hillsboro, OR) system is applied (Figures 6-16 and 6-17). Clamp compression is adjusted so that the pedal pulses remains palpable (or present on Doppler examinations if it was not palpable prior to the procedure). Gradual clamp release (2–3 mm every 20 minutes) is started after 90 minutes of compression if no bleeding is encountered.

A low-dose heparin (600–800 U/hr) infusion is started after the partial

Table 6-3. Percutaneous cardiopulmonary bypass support cannulae removal protocol

Remove cannule once ACT is <240 seconds
Manual compression for 15–20 minutes
Full clamp compression for 90 minutes
Gradual release of clamp: 2 mm every 15–20 minutes

ACT = activated clotting time.

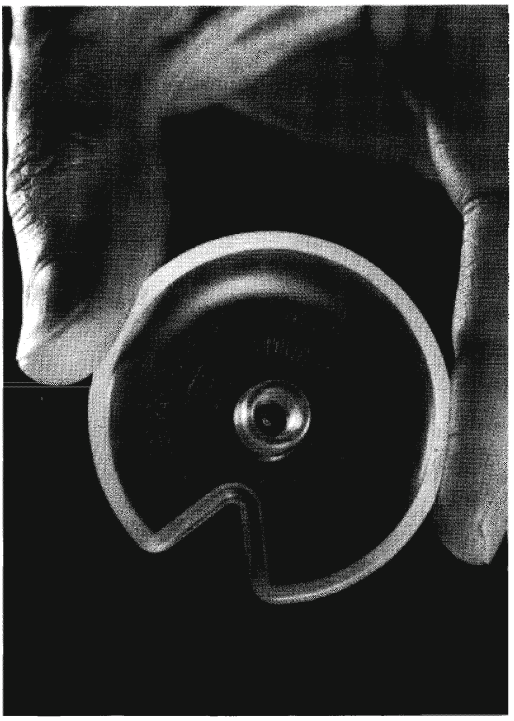

Figure 6-16. Compression disc used for hemostasis.

thromboplastin time declines to <70 seconds, or the activated clotting time declines to ≤180 seconds, and is continued until the patient is fully ambulatory. The angioplasty sheath and the Swan-Ganz catheter are removed the following day. Most patients are discharged at ≥72 hours after the procedure.

TERMINATION OF CARDIOPULMONARY BYPASS SUPPORT (EMERGENT GROUP)

In patients with cardiogenic shock who have undergone PTCA, termination of bypass support is similar to the elective group. However, in this group of patients weaning may take longer than in the elective group. Bypass cannulae can be left in place for up to 24 hours or longer (with full heparinization) if late instability appears likely.

In the cardiac arrest group, cannulae are left in place until definitive therapy is performed (PTCA or coronary bypass surgery). If patients are sent to emergency coronary bypass or other surgical procedures, PCPS is terminated

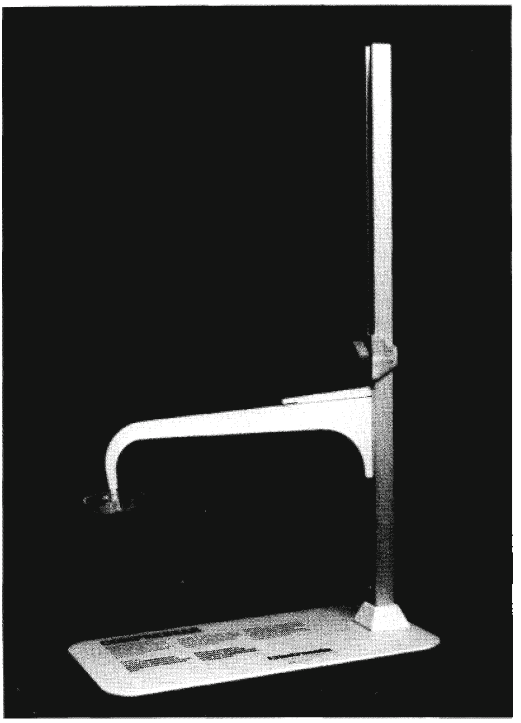

Figure 6-17. Compression clamp with lock and disc in place.

after conventional bypass (right atrium to aorta) is instituted. In these patients, the femoral bypass cannulae are removed by the surgeon after the completion of the surgical procedure, and the femoral artery and vein are sutured under direct vision. Patients in whom neither PTCA nor coronary bypass is possible are transferred to the coronary care unit on bypass. In this group, every effort is made to get the patient off bypass in less than 6–7 hours. Other circulatory support (e.g., intraaortic balloon pump) may be necessary to help wean the patient from PCPS.

OBSERVATION ON CARDIOPULMONARY BYPASS SUPPORT DURING ELECTIVE INTERVENTION

Once cardiopulmonary bypass support is instituted and the flow is increased, the patients usually complain of generalized warmth, and in some cases, feelings of nausea. Administration of 5 mg of compazine given intravenously prior to the initiation of cardiopulmonary bypass has substantially reduced the

incidence of nausea. Nausea has also been substantially reduced by starting the flow at 0.5 l/min and increasing by 0.5 l/min every 30 seconds until a flow rate of 2 l/min is achieved. With the current use of 18 Fr cannulae, a flow up to 5 l/min can be achieved if the patients are well hydrated prior to the procedure.

With the initiation of cardiopulmonary bypass support, there is a rapid fall (over a few minutes) in the filling pressures, manifested by a reduction in the pulmonary capillary wedge pressure (or pulmonary diastolic pressure). There is also a reduction in the systolic arterial blood pressure, with a slight increase in diastolic pressure, the latter feature known to be present with a nonpulsatile flow (see Figures 6-12 and 6-13). Echocardiography performed during cardiopulmonary bypass support demonstrates a reduction in the left atrial and left ventricular dimension. These observations, together with the reduction of the preload (see Figure 6-12D) and afterload, suggest that PCPS reduces myocardial oxygen demand, which may be responsible, in part, for the absence of angina during balloon inflation in most patients undergoing supported angioplasty. Nonetheless, segmental wall motion abnormalities and reduced pulse pressure (see Figure 6-12D) are present during balloon inflation, indicating ischemia distal to the occlusion.

The patient may experience numbness and tingling in the leg when PCPS cannulae are inserted. In such cases, sedation in the form of intravenous diazepam or morphine may be necessary. In some cases, intravenous nitroglycerin or sublingial nifedipine (as vasodilator) may be helpful to counteract any spasm, particularly when iliofemoral angiography has revealed a good caliber vessel prior to cannulation. Also, in patients with good-caliber iliofemoral vessels, such complaints may disappear spontaneously.

The flow rate that is necessary depends upon whether the patient is on complete or partial bypass (left ventricle still ejecting while on bypass). During partial bypass, in elective patients undergoing high risk PTCA, the average flow rate necessary is about 3.0 l/mm [18]. In cardiogenic shock, the average flow requirement has been 4.0 l/min [19]; while in cardiac arrest (full bypass support), it is 4.8 l/min [20]. The average bypass time during elective high risk angioplasty has been 37 minutes, 1.8 hours during cardiogenic shock, and 2.7 hours during cardiac arrest [20].

With the initiation of cardiopulmonary bypass support, pulmonary artery and systolic blood pressure decline (see Figures 6-12 and 6-13). In the elective group, as well as in cardiogenic shock patients, pulmonary capillary wedge (or pulmonary artery diastolic) pressure declines to 0–5 mmHg in 90% of patients.

Patients with very poor left ventricular function and severe pulmonary hypertension, and patients with prolonged cardiac arrest, are among those in whom complete unloading is not possible. These patients may benefit from left ventricular venting. Also, when cardiopulmonary bypass flow is commenced, it may take a few minutes before a decline in the left ventricular filling pressure occurs (see Figure 6-12C).

In some patients, significant hypotension (defined as mean a blood pressure of 60 mmHg; lower if the patient is awake) may occur during bypass or when increasing the flow rate. This is more common and pronounced in patients who are volume depleted or have low filling pressures in the setting of a dilated poorly functioning left ventricule. Therefore, it is imperative to have adequate filling pressures prior to the institution of bypass flow. If the patient's pulmonary artery diastolic pressure (or pulmonary capillary wedge) is less than 8–10 mmHg, volume can be given rapidly through the bypass perfusion circuit when the flow rate is inadequate. Urinary output increases after the institution of PCPS. Therefore, inserting a Foley catheter prior to the procedure is necessary.

In most patients in whom PCPS is terminated in the catheterization laboratory, volume infusion of 150–1000 cc (through the bypass system) is necessary prior to termination of PCPS. Recently 25% albumin (75–100 cc) has been given at the start of the procedure through the pump, resulting in a dramatic decrease in the volume requirement during the procedure.

OBSERVATION AFTER THE TERMINATION OF BYPASS SUPPORT

Some patients may complain of numbness and a tingling sensation in the leg when cannulae are still in place, while waiting for the activated clotting time to fall below 240 seconds in the coronary care unit. Such patients may require sedation, as well as vasodilators (i.v. nitroglycerin or S/L nifedipine). Interestingly, these complaints are usually transient, disappearing in an hour or so. Observation is safe so long as there is good capillary filling.

The total clamp compression time necessary for hemostasis using the current method is less than 3 hours, with maximum compression for 90 minutes followed by a subsequent gradual release over the next 90 minutes.

COMPLICATIONS

The complications due to PCPS are listed in Tables 6-4 and 6-5. Only one complication (repair of a femoral artery in a patient in the emergent group) was encountered in the last 33 patients in this series using the current cannula removal technique (Figure 6-18). Also, the requirement for blood transfusion

Table 6-4. Percutaneous cardiopulmonary bypass: Complications in 129 procedures (elective and emergent) requiring local surgery

Pseudoaneurysm	6[1]
Enlarging hematoma	3
Infection	2
Embolus to popliteal artery	1
Arteriovenous fistula	1
Total	13 (11%)

[1] Noted on follow-up.

Table 6-5. Percutaneous cardiopulmonary support: Complications in 129 procedures (elective and emergent), nonsurgical

Minor superficial skin infection	6
Femoral nerve weakness	5[1]
Superficial skin necrosis	5[1]
Minor gastrointestinal bleeding	2
Deep venous thrombosis	1
TIA (48 hours postprocedure)	1
Air embolus	1
Diabetic ketoacidosis	1
Total	22 (18%)

TIA = transient ischemic attack.
[1] Due to clamp (early experience), none in the current series using new cannulae removal protocol.

has been significantly reduced with the current method, as well as with the use of a cell saver (Figure 6-19).

There is no evidence of significant hemolysis or thrombocytopenia even when bypass support is extended to 6 hours.

COMMENTS

In the author's experience, the percutaneous cardiopulmonary bypass support procedure is feasible and has an acceptable morbidity. In spite of the high-risk patient population, there has been no mortality directly due to PCPS.

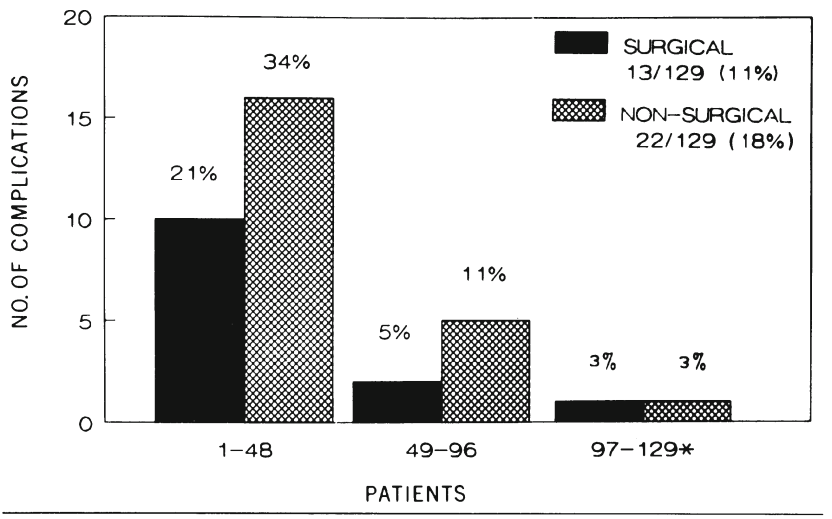

Figure 6-18. Complication rate for elective and emergent procedures (129 procedures). A marked reduction in the complication is noted in the last 33 cases using the current cannula removal technique.

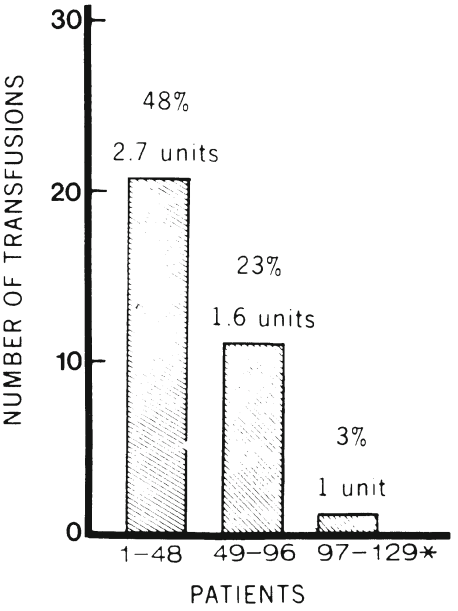

Figure 6-19. Significant reduction in transfusion requirement in the last 33 procedures using the current cannula removal technique.

The most common complications due to PCPS occur at the cannulae site. The local complications usually occur after the removal of the bypass cannulae. In our initial series (first 78 elective cases), bypass cannulae were removed in the catheterization laboratory once the patient was considered clinically, as well as hemodynamically, stable. Since patients had received a large bolus of heparin before the initiation of cardiopulmonary bypass, there still remained a large amount of circulating heparin at the time of cannulae removal. With the technique of early cannulae removal, it took a longer time for hemostasis, using external clamp compression. Because of this prolonged clamping (Figure 6-20), there were significant local complications, as well as a need for blood transfusion. None of the complications that occurred in the entire series were life threatening.

With the current method of cannulae removal, local complications have been markedly reduced (Figure 6-21) because by the time cannulae are removed, there is a lesser amount of circulating heparin, allowing rapid hemostasis (<2 hours) and less external clamp compression time (full compression requirement of ≤ 90 minutes). Also, the current cannulae removal technique allows reinstitution of cardiopulmonary bypass in the coronary care unit in the event of any hemodynamic compromise due to abrupt closure. This would not be

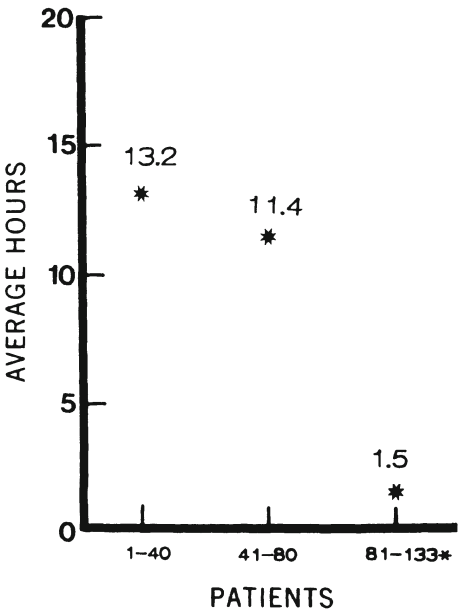

Figure 6-20. Duration of clamp compression in the entire series of 133 procedures. Note the dramatic decrease in the necessary clamp time in the last 53 procedures using the current cannula removal technique.

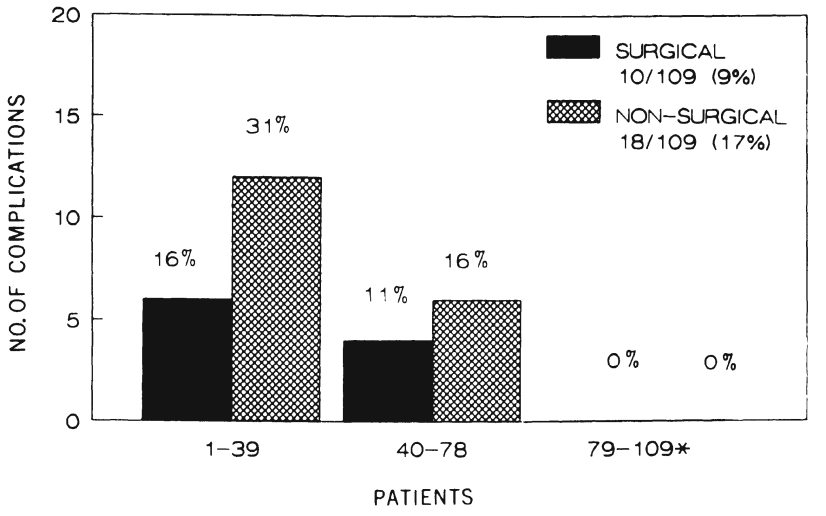

Figure 6-21. Elimination of local complications in the last 31 elective procedures using the current cannula removal technique.

possible if the vessels were sutured surgically after the completion of the procedure.

Femero-femoral cardiopulmonary bypass support, instituted percutaneously in the catheterization laboratory, makes interventional procedures feasible in patients who were not previously candidates. Also, PCPS reduces operator anxiety, allowing the achievement of an optimal result. If necessary, the patient can be taken to the operating room in a hemodynamically stable condition should abrupt closure occur during supported PTCA. Otherwise, these high risk patients may not survive long enough to reach the operating room.

Currently, PCPS is the only circulatory support system capable of maintaining cardiopulmonary function, even in the absence of an intrinsic cardiac rhythm that is practical in the catheterization laboratory. Also PCPS permits prolonged balloon inflation, which may reduce restenosis and improve immediate results [24].

However, we and others have indicated that PCPS does not eliminate ischemia distal to an occlusion. Therefore, should abrupt closure occur that is not amenable to repeat PTCA, patients should undergo immediate coronary bypass surgery. Coronary perfusion in such patients, using a separate roller pump, is under investigation and may eliminate ischemia distal to the occlusion. If adequate coronary perfusion distal to an occluded vessel is established, then this form of support may be the most ideal, "total cardiopulmonary bypass support."

PCPS provides adequate systemic perfusion, even in the absence of an intrinsic cardiac rhythm, and is therefore superior to currently available support devices, such as the intraaortic balloon pump [25]. The capability of PCPS to provide hemodynamic support in patients with cardiogenic shock or cardiac arrest has been impressive [19,20]. The hemodynamic stability achieved with PCPS allowed these patients to undergo complex PTCA or coronary bypass surgery, resulting in improved survival that was greatest when PCPS was instituted early, followed by definitive therapy [20].

PCPS differs from the traditional cardiopulmonary bypass system in that it actively aspirates the blood directly from the right atrium using a vortex pump rather than gravity drainage (Figure 6-22). Because of this, 5–6 l of blood flow per minute can be achieved through 18–20 Fr cannulae. When used by a properly trained team, this system is safe from the introduction of air, since any massive amount of air will lock the centrifugal pump. Also, small amounts of air from the venous site are trapped by the membrane oxygenator. Furthermore, the low-pressure nature of the system makes it relatively safe from cavitation or explosion. Because of the ease of setup and the compact size, it is well suited for use in the catheterization laboratory.

There are two major advantages of institution of cardiopulmonary bypass support using the percutaneous femoral approach described here. First, the technique of cannulae placement is simple and requires no extraordinary skill from an interventionalist. Definition of iliofemoral anatomy by angiography,

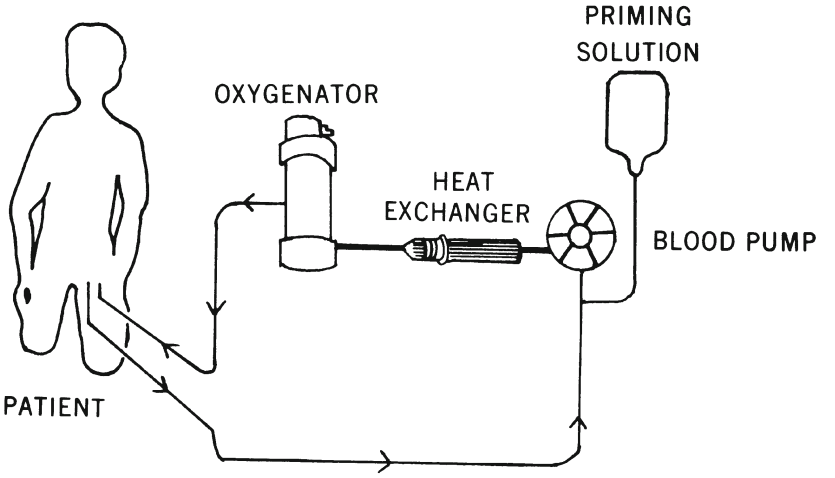

Figure 6-22. Schematic of the cardiopulmonary bypass support system showing active aspiration of venous blood by a vortex pump with subsequent passage of blood through the heat exchanger to the membrane oxygenator and return to the patient.

which is obtained routinely prior to elective supported interventions, also enhances safety by reducing the likelihood of vascular injury. Also, in patients who have sustained cardiac arrest, cannulae can be placed while cardiopulmonary resuscitation is in progress. The second advantage of this approach is that by leaving the cannulae in for 5–7 hours (while waiting for the activated clotting time to drop below 240 seconds), any hemodynamic compromise during this period can be immediately reversed by restarting PCPS.

There are, however, three limitations (Table 6-6) of PCPS, which include incomplete left ventricular unloading, particularly after a prolonged cardiac arrest; ischemia distal of an occluded vessel; and an inability to use the system for more than 6 hours. Also, the use of 18 Fr cannulae requires exclusion of patients with significant iliofemoral disease.

Other modalities, however, may be useful in the support of high risk angioplasty. The intraaortic balloon pump has been used, but is ineffective in patients in cardiac arrest or those in whom left ventricular function is sufficiently compromised. The hemopump may provide adequate support, even in patients with profound dysfunction [26]. At present, however, the device

Table 6-6. Percutaneous cardiopulmonary bypass support limitations

Incomplete left ventricular unloading
Lack of coronary perfusion distal to coronary occlusion
Inability to use for prolonged periods

requires surgical insertion. Also, the necessity of placing the device across the aortic valve may make it difficult to use in the setting of cardiac arrest.

Antegrade or retrograde perfusion catheters that provide blood flow to myocardium served by an occluded vessel may maintain adequate blood flow following abrupt closure or during balloon inflation [27–30]. These devices may prove useful when used alone or may be an effective adjunct to PCPS. However, because of a rather large profile, coronary perfusion catheters may not be feasible in tortuous vessels or in distal lesions. Also, such catheters require a mean pressure of at least 70 mmHg for adequate perfusion. All of the current support modalities, including PCPS, are in a state of evolution, and the ultimate role of each remains to be defined [31].

FUTURE DIRECTIONS

It appears that there are two major limitations to PCPS. The first is incomplete left ventricular unloading, which is present following prolonged cardiac arrest, with severe global ischemia, severe pulmonary hypertension, and in patients with severe left ventricular failure. One of the approaches to this limitation could be left ventricular venting, which can be accomplished by pump aspiration through a specially designed pigtail catheter placed in the left ventricle (Figure 6-23) or by retrograde [32] venting of the pulmonary artery (by making the pulmonic valve incompetent). In our experience, it appears that defibrillation of patients with prolonged cardiac arrest is facilitated by left

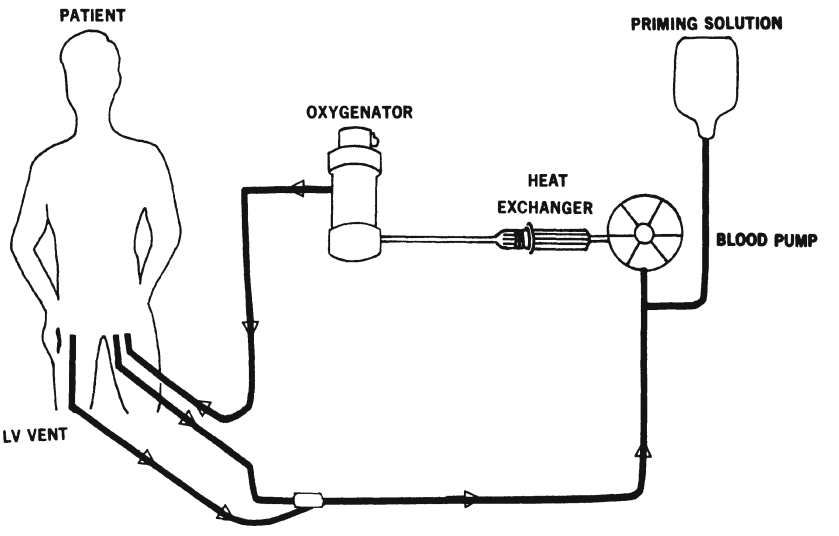

Figure 6-23. Schematic of the cardiopulmonary bypass support system showing the technique of left ventricular venting.

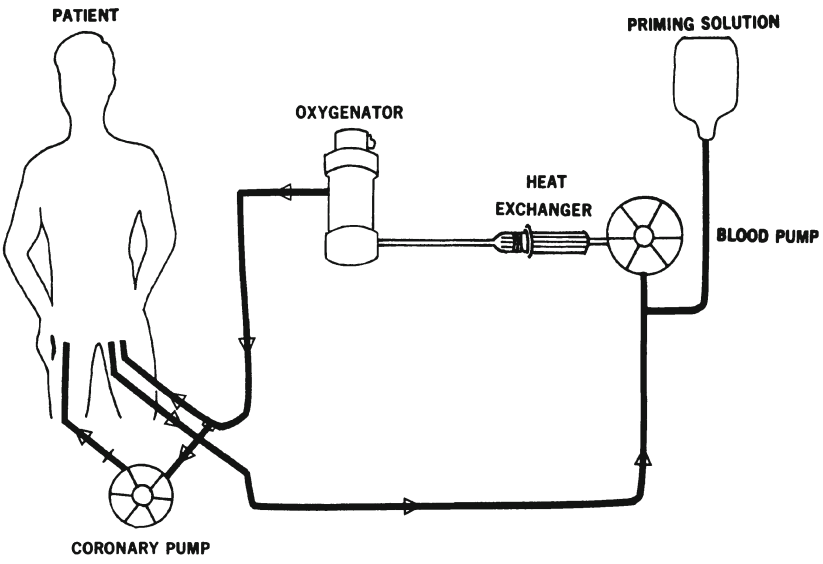

Figure 6-24. Schematic of the cardiopulmonary bypass support system showing the technique of coronary perfusion (distal to coronary occlusion) using a separate roller pump.

ventricular venting. Left ventricular venting may also prove useful in the reduction of left ventricular myocardial oxygen consumption during acute myocardial infarction. Recent evidence suggests that myocardial reperfusion in an unloaded state [33], as well as after the institution of cardioplegia [34], may prevent reperfusion injury. Whether similar results can be achieved during PTCA for acute myocardial infarction requires further study.

The second limitation is the absence of perfusion distal to an occlusion. This may be remedied by using a separate roller pump to provide continuous antegrade perfusion (Figure 6-24) or by using currently available autoperfusion catheters. Lack of distal perfusion is of concern only if a vessel closes acutely during PTCA and flow is not reestablished quickly.

The combination of venting and antegrade coronary perfusion in conjunction with PCPS may provide a improved degree of circulatory support. The role of PCPS as a bridge to other left ventricular assist devices or cardiac transplantation requires evaluation.

CONCLUSIONS

A safe and easily applied technique of percutaneous cardiopulmonary bypass support has been developed for use in the cardiac catheterization laboratory. The importance of this technique lies in its ability to maintain hemodynamic stability during high risk interventional procedures regardless of intrinsic

cardiac function. Eighteen French venous and arterial cannulae are inserted percutaneously over a stiff guidewire after sequential dilatation with 12 Fr and 14 Fr dilators. Bypass flow rates up to 5 l/min can be achieved.

This technique can be applied to support patients with cardiac arrest, hemodynamic collapse following abrupt closure during coronary angioplasty, cardiogenic shock, and those undergoing high risk elective angioplasty. This form of support also permits the transport of patients to the operating room in a stable condition following a failed angioplasty. The complications are mostly related to cannulae removal and can be minimized or eliminated by the use of proper technique. Although the ultimate role of this new technique remains to be completely defined, it appears that it will expand the patient population in whom coronary interventions can be applied.

ACKNOWLEDGMENTS

The excellent contributions of my colleague, Dr. Michael J. Domanski, in the preparation of this manuscript is greatfully recognized. The contributions of the Interventional Cardiology Team of Washington Adventist Hospital are greatly appreciated. The secretarial assistance of Grace Murtagh and Linda Corridon are also very much appreciated.

REFERENCES

1. Gruentzig AR. Transluminal dilatation of coronary artery stenosis. *Lancet* 1978; 1:263–266.
2. Gruentzig AR, Senning A, Seigenthaler WE. Nonoperative dilatation of coronary artery stenosis: Percutaneous transluminal coronary angioplasty. *N Engl J Med* 1979; 301:61–68.
3. Cowley MJ, Vetrovec GM, DiSciascio G, Lewis SA, Hirsch PA, Wolfgang TC. Coronary angioplasty of multiple vessels: Short-term outcome and long-term results. *Circulation* 1985; 72:1314–1320.
4. Quigley RJ, Erwin J, Maurer BJ, Walsh MJ, Gearty GF. Percutaneous transluminal coronary angioplasty in unstable angina: Comparison with stable angina. *Br Heart J* 1986; 55:227–230.
5. Holmes DR, Vliestra RE. Percutaneous transluminal coronary angioplasty: Current status of future trends. *Mayo Clin Proc* 1986; 61:865.
6. Dorros G, Cowley MJ, Janke L, Kelsey SF, Mullin SM, Van Raden M. In-hospital mortality rate in the National Heart, Lung and Blood Institute Percutaneous Transluminal Coronary Angioplasty Registry. *Am J Cardiol* 1984; 53:17C–21C.
7. Cowley MJ, Dorros G, Kelsey SF, Van Raden M, Detre KM. Acute coronary events associated with percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1984; 53:12C–16C.
8. Bredlau CE, Roubin GS, Leimgruber PP, Douglas JS Jr., King SB III, Gruentzig AR. In-hospital morbidity and mortality in patients undergoing elective coronary angioplasty. *Circulation* 1985; 72:1044–1052.
9. Cowley MJ, Dorros G, Kelsey SF, Van Raden M, Detre KM. Emergency coronary bypass surgery after coronary angioplasty: The National Heart, Lung, and Blood Institute's Percutaneous Transluminal Coronary Angioplasty Registry Experience. *Am J Cardiol* 1984; 53:22C–26C.
10. Vogel RA, Tommaso CL, Gundry Sr. Initial experience with coronary angioplasty and aortic valvuloplasty using elective semipercutaneous cardiopulmonary support. *Am J Cardiol* 1988; 62:811–813.
11. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous institution of cardiopulmonary (bypass) support: Technique and complications. *J Am Coll Cardiol* 1989; 13:159A.
12. Shawl FA, Domanski MJ, Wish MH, Davis M. Percutaneous cardiopulmonary bypass support in the catheterization laboratory: Technique and complications. *Am Heart J* 1990; 120: 195–203.
13. Lande HA, Edwards L, Bloch JH, et al. Clinical experience with emergency use of prolonged

cardiopulmonary bypass with membrane pump oxygenator. *J Thorac Sur* 1970; 10:409–423.
14. Baird RJ, Rocha AJ, Miyagishimart, et al. Assisted circulation following myocardial infarction: A review of 25 patients treated before 1971. *Can Med Assoc J* 1972; 107:287–291.
15. Mattox KL, Beall AC. Application of portable cardiopulmonary bypass to emergency intrumentation. *Med Instrum* 1977; 11:347–349.
16. Phillips SJ, Ballentine B, Slonined, et al. Percutaneous initiation of cardiopulmonary bypass. *J Thorac Surg* 1983; 36:223–225.
17. Kanter KR, Binington DG, Vandormael M, et al. Emergency rescusitation with extracorporeal membrane exygenation for failed angioplasty (abstr) *J Am Coll Cardiol* 1988; 11:149.
18. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous cardiopulmonary bypass support in high risk patients undergoing percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1989; 64:1258–1263.
19. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Emergency percutaneous cardiopulmonary bypass with cardiogenic shock from acute myocardial infarction. *Am J Cardiol* 1989; 64:967–970.
20. Shawl FA, Domanski MJ, Wish MH, Davis M. Punja S. Hernandez TJ. Emergency cardiopulmonary bypass support in patients with cardiac arrest in the catheterization laboratory. *Cathet Cardiovasc Diag* 1990; 19:8–32.
21. Shawl FA. Percutaneous cardiopulmonary bypass support in high risk coronary angioplasty. *Cardiol Clin* 1989; 87:865–875.
22. Shawl, FA. Percutaneous cardiopulmonary bypass support in high risk interventions. *J Invas Cardiol* 1989; 5:287–293.
23. Vogel RA, Shawl FA, Tammasco C. O'Neill W, Overlie P, O'Toole J, Vandormael M, Topol W, et al. Initial report of the National Registry of Elective Cardiopulmonary Bypass Supported Angioplasty. *J Am Coll Cardiol* 1990; 15:23–29.
24. Kaltenbach M, Beyer J, Walter S. Klepzig H, Schmidts L. Prolonged application of pressure in transluminal coronary angioplasty. *Cathet Cardiovasc Diag* 1984; 10:213–219.
25. Alcan KE, Stertzer SH, Walsh JE, DePasquale NP, Bruno MS. The role of intra-aortic balloon counterpulsation in patients undergoing percutaneous transluminal coronary angioplasty. *Am Heart J* 1983; 105:527–530.
26. Smalling RW, Cassidy DB, Merhige M, Felli PR, Wise GM, Barrett RL, Wampler RD. Improved hemodynamic and left ventricular unloading during acute ischemia using the left ventricular assist device compared to intraaortic balloon counterpulsation (abstr). *J Am Coll Cardiol* 1989; 13:160.
27. Corday E, Meerbaum S, Dorey JK. The coronary sinus: Alternative channel for administration of arterial blood and pharmacological agents for protection and treatment of cardiac ischemia. *J Am Coll Cardiol* 1986; 7:711–714.
28. Drury JK, Yamazaki S, Fishbein MC, Meerbaum S, Corday E. Synchronized diastolic coronary sinus venous retroperfusion: Results of preclinical safety and efficacy study. *J Am Coll Cardiol* 1985; 6:328–335.
29. Lehman KG, Atwood JE, Snyder EL, Ellison RL. Autologens blood perfusion for myocardial protection during coronary angioplasty: A feasibility study. *Circulation* 1987; 76:312–323.
30. Hinohara T, Simpson JB, Philips HR, Stack RS. Transluminal intracoronary perfusion catheter. A device to maintain coronary reperfusion between failed angioplasty and emergency coronary bypass surgery. *J Am Coll Cardiol* 1988; 11:977–982.
31. Topol EJ. Emergency strategies for failed transluminal coronary angioplasty. *Am J Cardiol* 1989; 63:249–250.
32. Kolobow T, Rossi F, Borelli M, Foti G. Long-term closed chest partial and total cardiopulmonary bypass by peripheral cannulation for severe right and/or left ventricular failure. The use of a percutaneous spring in pulmonary artery position to decompress the left heart. *Trans Am Soc Artif Intern Organs* 1988; 345:485–489.
33. Laschinger JC, Grossi, EA, Cunningham JN, et al. Adjunctive left ventriuclar unloading during myocardial reperfusion plays a major role in minimizing myocardial infarct size. *J Thorac Cardiovasc Surg* 1985; 90:80–85.
34. Allen BS, Okamoto F, Buckberg GD, et al. Studies of controlled reperfusion after ischemia. Improved functional recovery after 6 hours of regional ischemia by careful control of conditions of reperfusion and composition of reperfusate. *J Thorac Cardiovasc Surg* 1986; 92(Suppl): 621.

7. PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT IN PATIENTS UNDERGOING "HIGH RISK" CORONARY ANGIOPLASTY

FAYAZ A. SHAWL

INTRODUCTION

Percutaneous transluminal coronary angioplasty (PTCA) has been practiced in the United States for a little over a decade [1]. In the past 10 years, we have witnessed a tremendous growth in the number of PTCA procedures performed in the United States and elsewhere. In 1989 alone there were at least 300,000 PTCA procedures performed in the United States and an additional 150,000 performed in other countries. The reason for such a tremendous growth in the number of PTCA procedures has been because of the relative ease of the procedure, its short hospital stay, and the rapid return to work compared with surgery. In addition, the level of hospital cost (even considering recurrences) and the tremendous favorable effect on productivity compared with surgery cannot be denied in this cost-conscious era.

Initially envisioned by Dr. Gruentzig, its creator, as an alternative to coronary bypass graft surgery for a selected subgroup of patients with single-vessel coronary artery disease and good left ventricular function [2], PTCA is now considered a legitimate approach for multivessel coronary artery disease, unstable angina, acute myocardial infarction (directly or following failed thrombolysis), and in symptomatic patients who have previously undergone coronary artery bypass graft surgery [3–7].

Despite this dramatic increase in the use of PTCA because of technological advances and increased operator experience, there remain certain limitations, including restenosis, old total occlusions, diffusely diseased vessels, abrupt vessel closure, and certain "high risk" patients.

Abrupt vessel closure occurs in approximately 5% [8,9] of patients undergoing elective PTCA, which can result in myocardial infarction, hemodynamic collapse, necessity for emergency bypass surgery, and death [10–13]. Because of this risk of abrupt closure, PTCA has been utilized primarily in single-vessel disease and in a selected group of multivessel coronary artery disease patients with normal or near normal left ventricular function.

Some patients are not considered candidates for PTCA because abrupt closure would result in hemodynamic collapse. Such patients are also at high risk for not surviving emergency coronary bypass graft surgery. Abrupt closure with hemodynamic compromise may not allow the use of other modalities, such as intracoronary stenting [14] or laser balloon angioplasty [15]. Patients at particularly high risk are those who have decreased left ventricular function and/or target vessel(s) supplying greater than one half of the remaining viable myocardium [16–18]. These patients may not even tolerate transient myocardial ischemia during balloon inflation [10]. Identification of such high risk angioplasty patients is reviewed by Dr. Ellis in Chapter 1.

PTCA has been applied in patients with a high risk profile (poor left ventricular function, left main or left main equivalent coronary stenosis, advanced age, large amount of myocardium at risk), but has been associated with high procedure-related morbidity and mortality, even in experienced hands [20–23]. The hemodynamic consequences of balloon inflation or abrupt closure in such high risk patients have prompted the use of circulatory support during PTCA [24].

In the past [25–29], PTCA in "high risk" patients has been accomplished by using a prophylactic intraaortic balloon pump. However, if hemodynamic collapse occurs as a result of abrupt closure, particularly when the patient has no intrinsic rhythm, the intraaortic balloon pump will not be effective. On the other hand, cardiopulmonary bypass support is reliable and effective in supporting such high risk patients because it can provide excellent circulatory support, even in the absence of an intrinsic rhythm (Figure 7-1).

To reduce the risk of hemodynamic instability, either during balloon inflation or in the event of an abrupt closure in such "high risk" patients, we and others [30–33] have reported the prophylactic use of cardiopulmonary bypass support in the catheterization laboratory. When cardiopulmonary bypass support is used in the catheterization laboratory prophylactially during high risk PTCA procedures, the term *supported angioplasty* has been applied [30–33]. This article discusses results obtained with supported angioplasty: acute outcome, complications, and follow-up.

PATIENT SELECTION FOR SUPPORTED ANGIOPLASTY

The basic indication for supported angioplasty is a severely symptomatic patient, in whom the risk of PTCA or coronary artery bypass graft surgery is extremely high, but in whom there is an approachable lesion or lesions. High

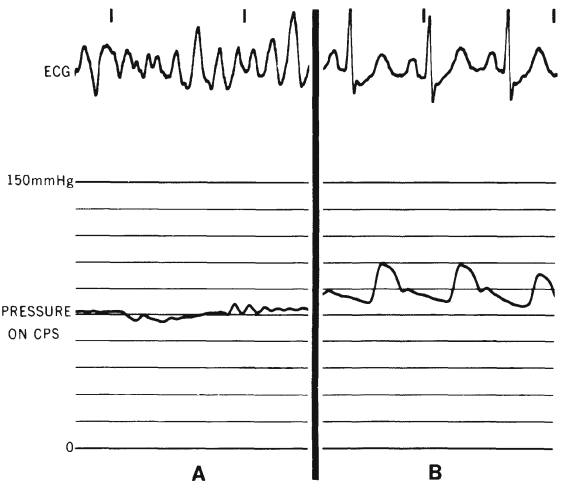

Figure 7-1. A 72-year-old man who developed refractory cardiac arrest following abrupt closure (dissection) of the left circumflex after coronary angioplasty. He had previously sustained anterior myocardial infarction due to totally occluded left anterior descending artery. *A*: Mean blood pressure 75 mmHg on cardiopulmonary bypass support at a flow rate of 5 l/min. Note that the ECG demonstrates ventricular fibrillation but the patient was awake and responsive to verbal commands. *B*: After defibrillation and prior to emergency coronary bypass graft surgery. From Shawl FA, et al. Emergency percutaneous cardiopulmonary bypass support in patients with cardiac arrest in the catheterization laboratory. *Cathet Cardiovasc Diag* 1990; 19:8–12. With permission.

operative risk based on severe left ventricular dysfunction, multiple previous bypass surgeries, advanced age, or associated medical illness may be present. The risk of PTCA is also extremely high in such patients, particularly those in whom the only remaining patent vessel is to be dilated. At times, it is impossible to determine which mode of therapy is preferable in these patients.

If patients are considered inoperable, emergency bypass surgery in the event of PTCA complication may be of no benefit. In such cases, who are truly deemed inoperable, the patient, his or her family's referring cardiologist, and the surgeon have all agreed that no emergency coronary bypass surgery would be available, even if the need arises. Occasionally, the patient may be a transplant candidate, in which case one may have to consider PCPS as a bridge to other left ventricular assist devices before a donor heart becomes available.

Patients are considered candidates for supported PTCA (Table 7-1) if they have severe (Canadian Cardiovascular Society Class III or IV) or unstable angina with poor left ventricular function (ejection fraction $\leq$25% and/or vessel(s) to be dilated supplying greater than one half of the remaining viable myocardium. There are, however, contraindications to supported angioplasty including when dilation of the target vessel is not technically feasible, or

Table 7-1. Inclusion criteria for supported PTCA

- Severe angina (Class III or IV) or unstable angina with poor LV function (EF ≤25% and/or target vessel(s) supplying >½ of the remining viable myocardium
- Culprit lesion amenable to PTCA

Table 7-2. Preangioplasty orders

1. Vital signs qid; temp bid.
2. Diet
3. Activity
4. Chest x-ray, PA & lateral only if not done within 2 months
5. Lab: CBC, hemostatic profile with consult by pathologist; SMA 18, cardiac isoenzymes, ABGs, and urinalysis
6. EKG
7. Notify blood bank that patient is to have angioplasty _____
8. Label chart "Allergic to: _____
9. Obtain surgical permit for: a) Coronary angioplasty by: _____
   b) Possible emergency coronary bypass by: _____
   c) Percutaneous heart-lung bypass by: _____
10. NPO after midnight except for medications or NPO after admission
11. To heart cath laboratory on call; premedicate with Valium 20 mg po or Demeral 50 mg and Valium 5 mg on call
12. NTG 0.4 mg S/L PRN for chest pain; repeat q3 minutes PRN. If not relieved in 5 minutes, call MD
13. Start i.v. in left arm of D5N with extension tubing at ___ a.m./p.m. @ ___ cc/hr.
14. Dextran-40 500 cc, start 50 cc/hr at ___ a.m./p.m. Check v.s. q2–5 minutes × 4 after starting infusion (unless pt. is in heart failure)
15. Medications: a) Tylenol grain × po q4 hr PRN
    b) Dalmane 30 mg po PRN sleep, repeat × 1 PRN
    c) MOM 1 oz, Dulcox suppository, or Fleet enema for constipation
    d) Isordil
    e) Ascripton
    f) Inderal
    g) Procardia
    h) Cardizem
16. Please insert Foley catheter
17. Call audiovisual dept. X-5048 to show film on angioplasty (Dr. Shawl's patients only, asap)

when the lesion is considered at high risk for abrupt closure (long, calcified, tortuous, eccentric, ulcerated lesions), particularly if the patient is not a candidate for coronary bypass graft surgery. Also, the presence of severe iliofemoral disease, or a history of bleeding diathesis, are contraindications.

When coronary bypass graft surgery is not an option in any circumstance, angioplasty should be undertaken only if an ideal lesion is present.

CASE EXAMPLE OF SUPPORTED ANGIOPLASTY

High risk PTCA

A 70-year-old woman with a history of previous anterior myocardial infarction (Figure 7-2) presented with unstable angina associated with transient

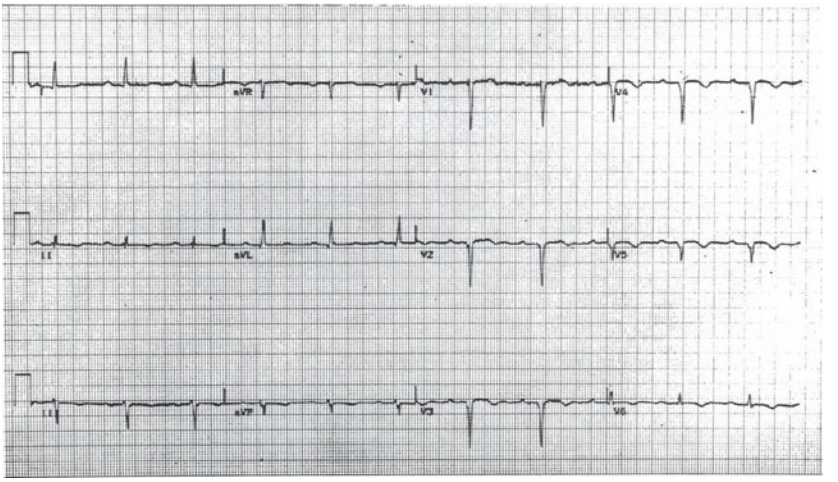

Figure 7-2. Twelve-lead resting electrocardiogram showing prior anterior myocardial infarction.

ST-segment depressions during chest pain. Cardiac catheterization revealed a moderate degree of pulmonary hypertension, a left ventricular ejection fraction of 25% and severely hypokinetic anterolateral and apical segments (Figures 7-3A and 7-3B). The patient had a history of moderate chronic obstructive lung disease and insulin-dependent diabetes. Coronary angiography revealed a totally occluded left anterior descending coronary artery prior to the first septal perforator, a small diffusely diseased left circumflex, and a critical stenosis in the distal right coronary artery prior to its bifurcation into the posterior descending and posterolateral artery (Figure 7-4A). The distal left anterior descending was seen filling from collaterals from the right coronary artery.

Both PTCA and coronary bypass were technically feasible in this patient. PTCA was selected as a substitute for surgery because the lesion was ideal for dilatation and because surgery did not offer any more complete revascularization of viable myocardium than PTCA. PTCA on PCPS was successful (Figure 7-4B) and the patient was discharged on the fourth day after the procedure following an uneventful hospital course.

High risk for CABG

A 67-year-old man was admitted with an acute inferior myocardial infarction and congestive heart failure. The patient had a prior history of liver disease and alcoholic cardiomyopathy, with multiple prior admissions for congestive heart failure. He had also had resection of one lobe of his lung for a carcinoma

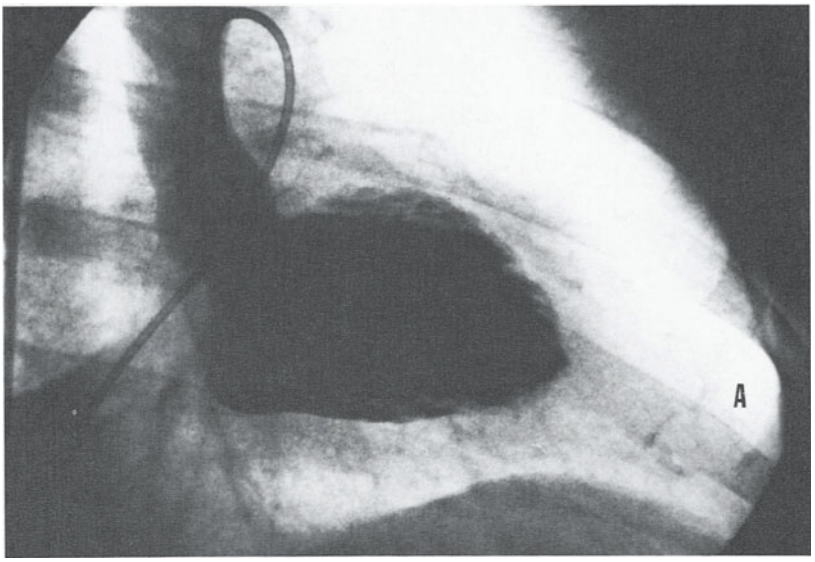

Figure 7-3A

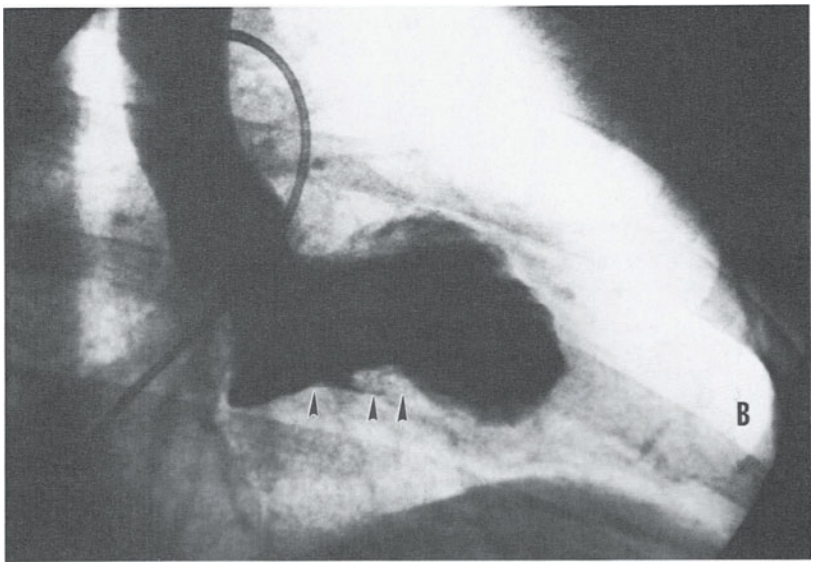

Figure 7-3B

Figure 7-3. *A, B*: Left ventriculography in the right anterior oblique view showing evidence of apical and anterolateral hypokinesis/dyskinesis with an ejection fraction of 25%. Note the preserved inferior wall motion (arrows).

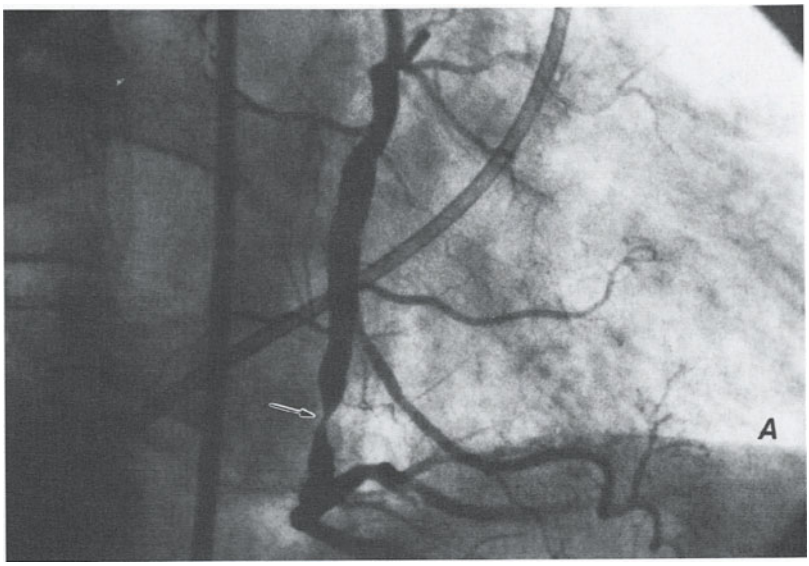

Figure 7-4A

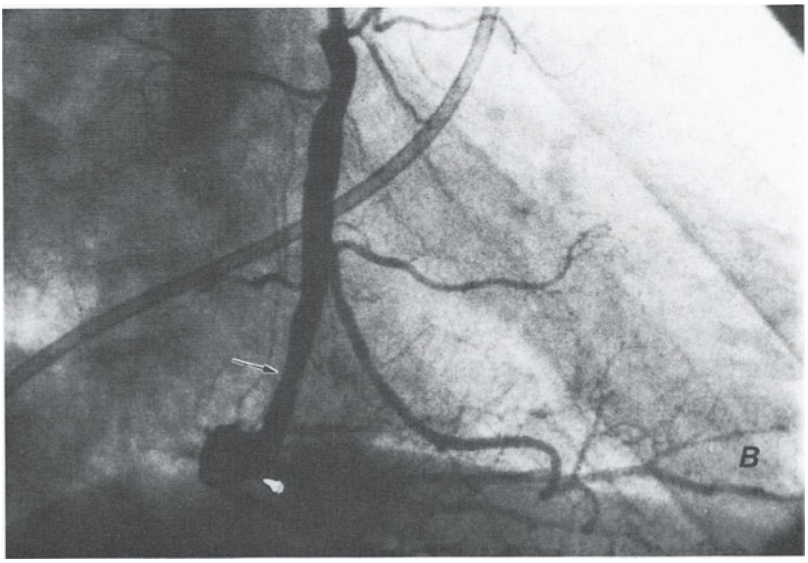

Figure 7-4B

Figure 7-4. Coronary angiogram of the right coronary and right anterior oblique view (A) before (arrow) and (B) after PTCA. The distal left anterior descending artery was seen filling through the collaterals from the right coronary artery, (not shown here).

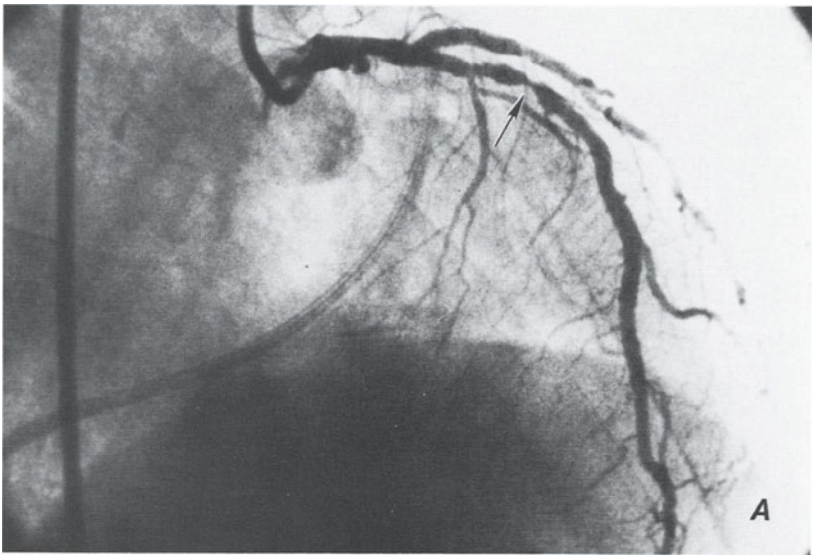

Figure 7-5A

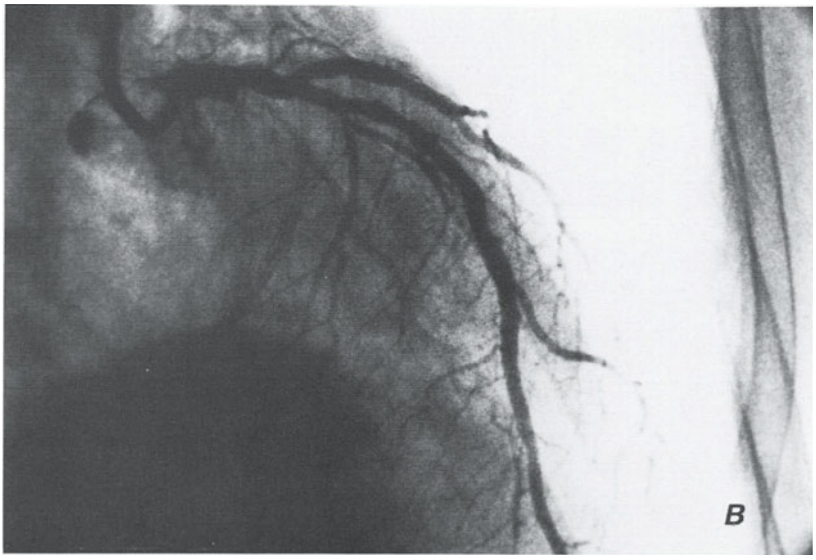

Figure 7-5B

Figure 7-5. A 67-year-old man with unstable angina due to critical mid (arrow) left anterior descending artery stenosis (A) who had a totally occluded left circumflex and right coronary artery (not shown here). After successful coronary angioplasty, the repeat coronary angiogram (B) shows an excellent angiographic result.

and had chronic obstructive lung disease due to a long history of heavy cigarette abuse. Because of postinfarction angina, he underwent cardiac catheterization, which revealed moderately severe pulmonary hypertension, elevated left ventricular end-diastolic pressure, and severe diffuse global hypokinesis, with a left ventricular ejection fraction of 15%. Coronary arteriography revealed proximal total occlusions of the right coronary and left circumflex and a critical narrowing in the mid-left anterior descending (LAD) coronary artery (Figure 7-5A).

Although surgery was technically feasible, if undertaken it would have been at very high risk. Therefore, supported angioplasty was decided upon.

Hemodynamics prior to bypass revealed a systemic blood pressure of 128/60 mmHg and PA pressure of 65/26 mmHg (Figure 7-6A), and a pulmonary capillary wedge pressure (PCW) of 25 mmHg (Figure 7-6B). PCPS

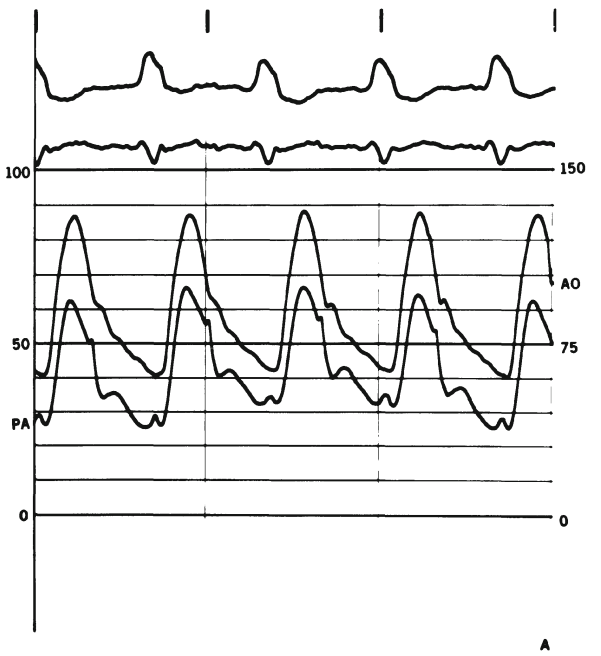

Figure 7-6A

Figure 7-6. Aortic (AO) and pulmonary artery (PA) pressures prior to bypass (A and B). Note reduction in the AO and PA pressures, PCW (C and D). During balloon inflation on bypass, the patient had no chest pain. Note there was no increase in PCW, but a reduction in pulse pressure was present (E), without much change in the diastolic AO pressure. PCW = pulmonary capillary wedge pressure.

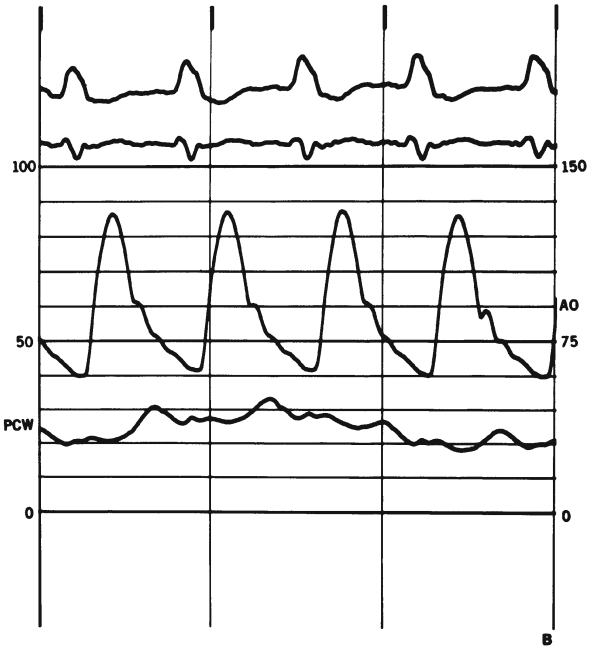

Figure 7-6B

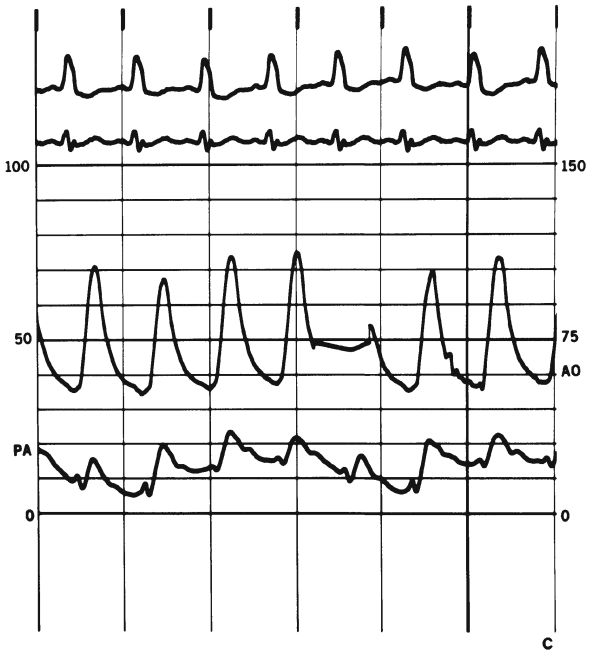

Figure 7-6C

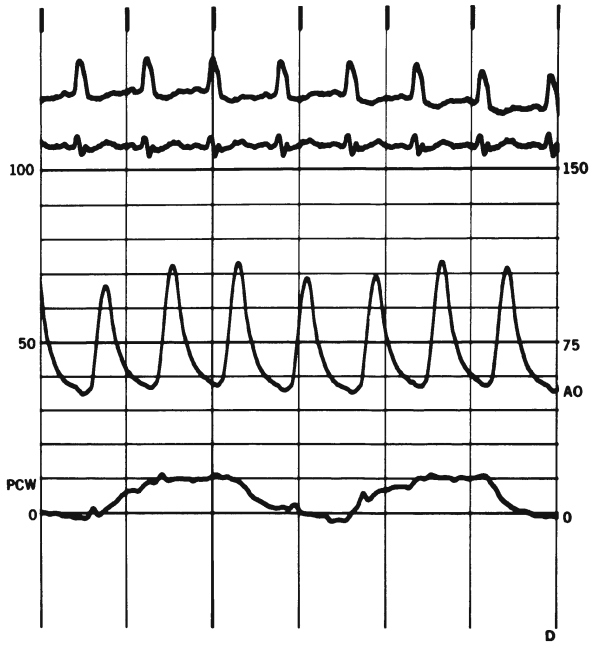

Figure 7-6D

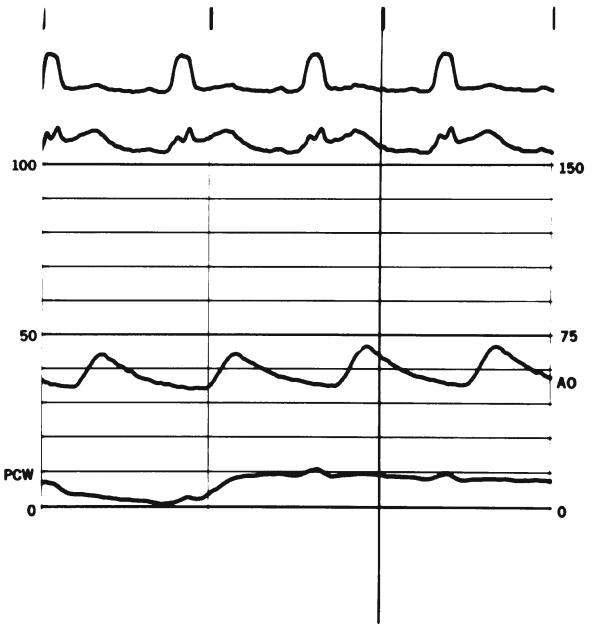

Figure 7-6E

flow was gradually increased to 3.0 l/min with a decrease in the systemic and PA pressures (Figures 7-6C and 7-6D). Next, PTCA of the mid-LAD was performed successfully using a prolonged balloon inflation of 5 minutes. The patient had no chest pain during the inflation and there was no increase in the PCW (Figure 7-6E).

During balloon inflation, there was a decrease in pulse pressure due to transient segmental left ventricular dysfunction without any change in the aortic diastolic pressure. Following balloon deflation, there was an immediate return of the pulse pressure to its baseline value. A repeat angiogram revealed an excellent result (Figure 7-5B).

Inoperable

A 76-year-old man with multiple prior myocardial infarctions presented with rest angina complicated by acute pulmonary edema and a history of multiple prior admissions for congestive heart failure. He also had a history of bilateral, severe carotid artery stenosis and cerebrovascular accidents with minimal residual right sided weakness. The patient had a history of colon resection for carcinoma and had a colostomy. He also had a history of long-standing, steroid-dependent asthma and renal insufficiency. Cardiac catheteriztion revealed a left ventricular ejection fraction of 18%. Coronary arteriography revealed critical ostial left main narrowing (Figure 7-7A) (only remaining patent segment) and a totally occluded LAD, left circumflex (LCX), and right coronary artery (RCA). The RCA, LCX, and LAD filled faintly and late by collaterals from the first septal perforator. He was seen in consultation by two surgeons, who refused to operate.

He had successful dilatation of the left main and tolerated balloon inflation (Figure 7-7B) up to 5 minutes without chest pain or elevation of the pulmonary artery diastolic pressure. Angiography post-PTCA revealed an excellent angiographic result, with brisk and early collateral filling of the entire coronary tree (Figure 7-7C). His subsequent hospital course was uneventful and he was discharged. Approximately 2 months later he was readmitted to another hospital with angina and pulmonary edema. Repeat angiography revealed restenosis at the ostium of the left main. CABG was subsequently performed at another institution, but the patient could not be weaned from cardiopulmonary bypass and expired.

Inoperable

A 56-year-old heavy smoker with severe, chronic lung disease and a history of prior CABG (left internal mammary graft to LAD, reversed saphenous vein grafts to an obtuse marginal branch and to the RCA) presented with refractory Class III angina despite maximal medical therapy. His previous CABG was complicated by an inferolateral myocardial infarction and sternal dehiscience, resulting in a prolonged hospitalization. Cardiac catheterization and coronary arteriography prior to supported PTCA revealed total proximal

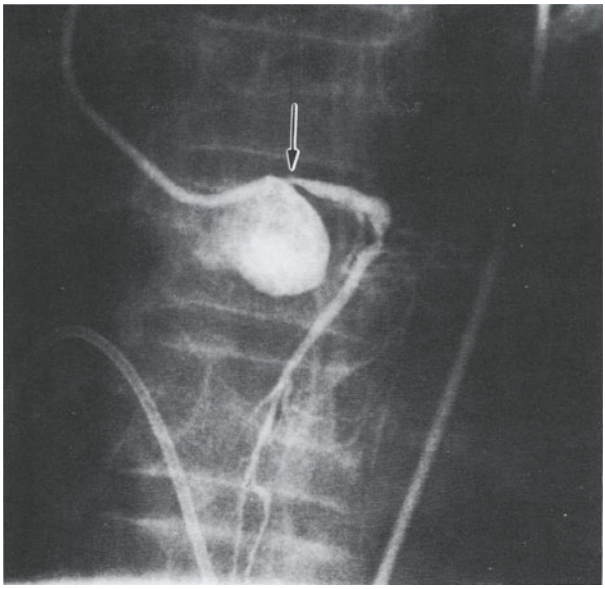

Figure 7-7A

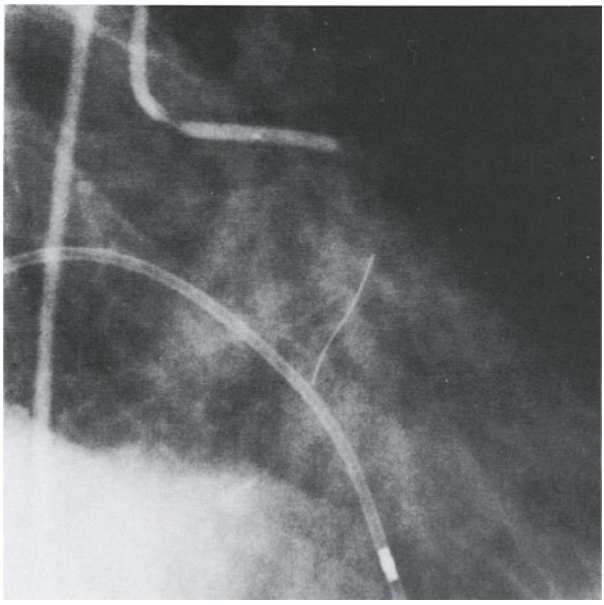

Figure 7-7B

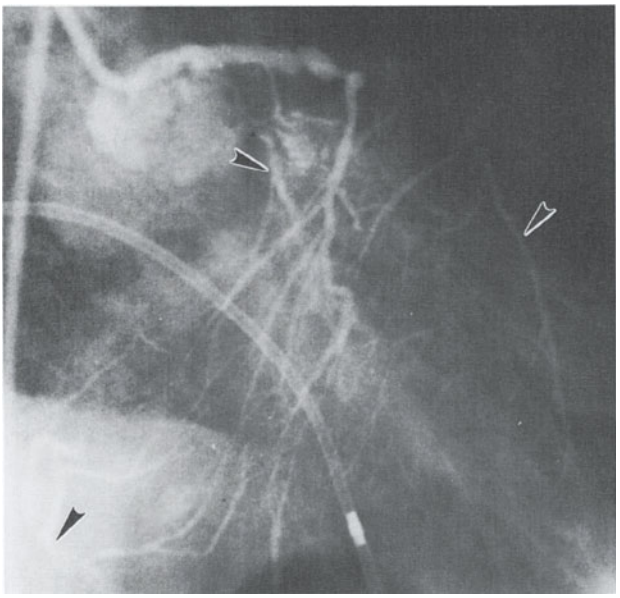

Figure 7-7C

Figure 7-7. A 76-year-old man undergoing dilatation of the only remaining vessel (left main). *A*: Prior to dilatation (arrow). *B*: Patient tolerated prolonged balloon inflation. *C*: Repeat angiogram demonstrates excellent results. Note the improved filling of all three major coronaries by ipsilateral collaterals (arrows). From Shawl FA. Percutaneous cardiopulmonary bypass support in high risk coronary angioplasty. *Cardiol Clin* 1989; 87(4):865–875. With permission.

occlusion of all three native coronaries and all grafts, except for the left internal mammary artery (LIMA), which had a subtotal stenosis (Figure 7-8A). Left ventriculography revealed an akinetic inferior wall and a mildy hypokinetic anteroapical region, with a left ventricular ejection fraction of 32%.

Two surgeons felt that the patient was inoperable because of the history of sternal dehiscience and severe lung disease. He underwent successful supported PTCA of the LIMA (Figure 7-8B). He was discharged on the fourth hospital day and remains asymptomatic 18 months later.

TECHNIQUE OF PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT (PCPS)

The detailed description of the technique for establishing PCPS during elective supported coronary angioplasty, which is termed *partial bypass support*, is fully

Figure 7-8. Coronary angiogram of left internal mammary artery, showing critical stenosis (arrow) at its anastomosis to the left anterior descending artery, the patient's only remaining vessel. A repeat coronary angiogram shows excellent results after PTCA (B).

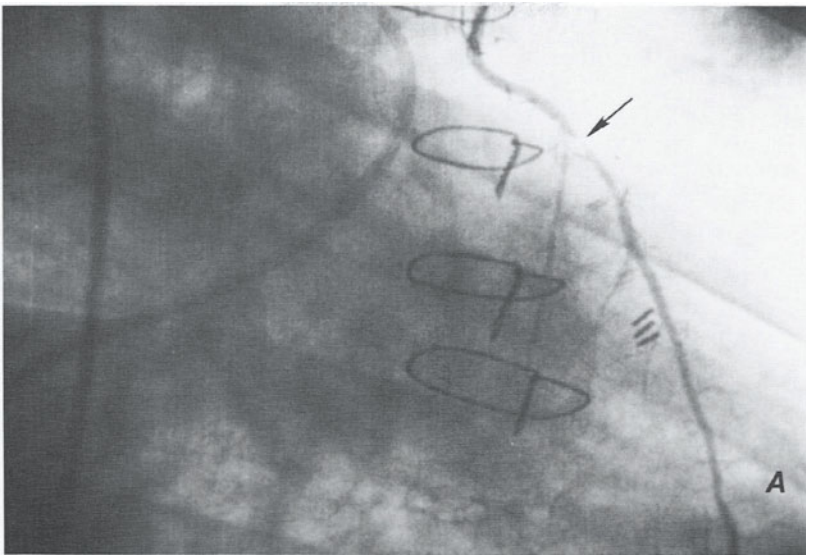

Figure 7-8A

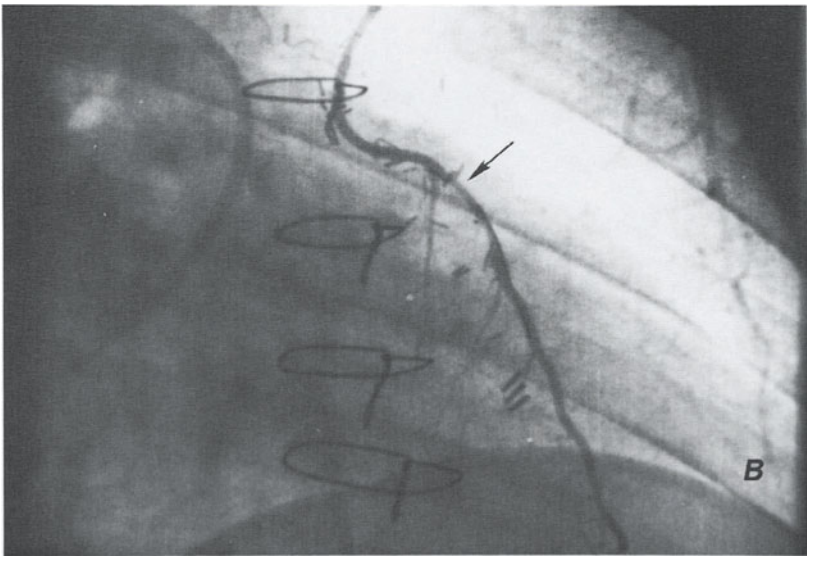

Figure 7-8B

described in Chapter 6. Basically, the patient received standard groin preparation and local anesthesia in the catheterization laboratory. Using the Seldinger technique, a 7 Fr pigtail catheter is introduced into the right femoral artery to perform iliofemoral angiography, visualizing first the left side and then, if necessary, the right side. If angiography of the left iliofemoral system reveals acceptable anatomy, a Swan Ganz thermodilution catheter is introduced into the right femoral vein for hemodynamic measurements before, during, and after PCPS. The 7 Fr pigtail catheter is then replaced by a standard 8 Fr angioplasty sheath. If the anatomy of left iliofemoral system is unsuitable for bypass cannulae, introduction is performed on the right side if acceptable anatomy is demonstrated by the right-sided iliofemoral angiography. Next, the left femoral system is entered and two standard 7 or 8 Fr sheaths are introduced into the vein and artery. Heparinization is accomplished by using 225 U heparin/kg body weight. Next, the arterial cannula is inserted using the author's technique described earlier (Chapter 6). Using a similar technique, an 18 Fr multihole venous cannula is inserted, and under fluoroscopy, the tip is positioned just above the junction of the right atrium and inferior vena cava. The cannulae are then connected to a portable cardiopulmonary bypass support system (CPS, C.R. Bard, Inc., Billerica, MA). After connecting this to the perfusion circuit, which has been primed with Normosol by the perfusionist, cardiopulmonary bypass flow is started and the activated clotting time (ACT) is measured 15 minutes later and kept $\geq$400 seconds with careful heparin dose titration.

INITIATION OF CARDIOPULMONARY BYPASS SUPPORT

How to initiate cardiopulmonary bypass flow prior and during PTCA is fully described in Chapter 6. Basically, the bypass flow is gradually increased to 2 l/min. The flow is then increased in increments of 0.5 l/min if the pulmonary capillary wedge pressure (or pulmonary artery diastolic pressure) is >5 mmHg or >50% of the baseline, or if the patient complains of chest pain with less than 2 minutes of balloon inflation.

TECHNIQUE OF PERCUTANEOUS TRANSLUMINAL CORONARY ANGIOPLASTY

The patient is premedicated with aspirin, 325 mg daily, before the procedure, when feasible (see Table 7-2). An infusion of low molecular weight dextran is started 3–4 hours prior to the procedure, at a rate of 60 cc/hr, unless the patient is in congestive cardiac failure. PTCA is then performed from the contralateral femoral artery using the standard technique. Angioplasty of the culprit vessel (the one considered to be the most important based on vessel size, area of myocardium in jeopardy, and lesion severity) is performed first. If successful, additional vessels are dilated, even though they supply an area of previous infarction.

Angiographic success is defined as a reduction of stenosis to <50% of the

luminal diameter narrowing. The culprit lesion is dilated for at least 2 minutes. Every effort is made to optimize the angiographic results, including the use of prolonged inflations (up to 10 minutes).

TERMINATION OF CARDIOPULMONARY BYPASS SUPPORT

After the completion of PTCA, cardiopulmonary bypass support is gradually weaned over 3–5 minutes and cannulae are clamped. Every effort is made to be certain that angiographic results following PTCA are excellent. If there is any doubt regarding the results following PTCA, repeat angiography should be performed 15–20 minutes later, prior to the termination of cardiopulmonary bypass support. Patients should be observed in the catheterization laboratory for an additional 15–30 minutes prior to transport to the coronary care unit.

A cell saver is used to transfuse the remaining blood in the bypass system into the patient. The patient is then placed on a special stretcher (Haustead, Marina, Ohio) and transferred to the coronary care unit. No further heparin is given to these patients, unless the PTT is ≤ 60, which usually occurs at ≥ 6 hours. Since these patients have received large doses of heparin, immediately prior to the institution of the cardiopulmonary bypass support, activated clotting time is checked every hour after the completion of autotransfusion. Once the ACT has dropped to less than 240 seconds, the cannulae are removed while the patient is still lying on the stretcher. After the cannulae are removed, manual compression is applied for 15 minutes. During this time, an assessment is made of the ideal position for subsequent clamp compression. Also, towards the end of 15 minutes, an assessment is made of the strength of the pedal pulses while still achieving good hemostasis. Then, an external clamp (Instromedix Compressar) using a new modified mushroom disc (Comfort Disc, Instromedix, OR) is used for 90 minutes. After 90 minutes, the clamp is gradually released over the next $1\frac{1}{2}$ hours, unless there is bleeding. Heparin is restarted once partial thromboplastic time (PTT) decreases to <70 seconds using 600 U/hr. The PTT is maintained between 55 and 70 seconds unless a thrombus was noted at the time of PTCA prior dilatation. Under these circumstances, PTT is kept between 70 and 100 seconds. Other post-CPS orders are found in Table 7-3. The angioplasty sheath, as well as the Swan Ganz catheter, are removed after 24 hours of observation in the coronary care unit. The patients are left on heparin for at least 48–72 hours. The patients are usually discharged 3 days after a successful supported PTCA.

FOLLOW-UP AFTER HOSPITAL DISCHARGE

Patients in our initial series underwent noninvasive Doppler flow studies 2–4 weeks after discharge to look for any evidence of vascular abnormality at the cannulae insertion site (evidence of pseudoaneurysm formation or arteriovenous fistula). Repeat cardiac catheterization with iliofemoral angiography was performed in the majority of patients between 4 and 6 months after the

Table 7-3. Post-supported angioplasty

LAB AND ROUTINE
1. ACT Q 1 hr after completion of autotransfusion until ≤ 240 sec
2. PTT Q 2 hr after completion of autotransfusion (coinciding with ACTs) until < 70 then, Q AM while on heparin
3. SMA 7 with first PTT then Q AM × 1
4. CBC in AM
5. H&H Q 8 hr × 3 upon completion of autotransfusion
6. Cardiac isoenzymes Q 6 hr × 4 (start with first PTT)
7. O_2 2 l nasal cannula or _____
8. ABGs upon arrival to CCU and in AM
9. 12-lead EKG upon arrival to CCU and in AM
10. Clear liquids 1st 8 hrs then advance to previous diet as tolerated

IVs
1. Maintenance i.v. D5NS (or NS if diabetic) at ____ cc/hr
2. Increase maintenance i.v. to 999 cc/hr for BP ≤ 90 mmHg systolic until 100 mmHg systolic as long as PAD < 16
3. Dextran at 50 cc hr until _____
4. Restart heparin at 600 U/hr when PTT 70 or below

MEDICATIONS
1. Resume pre-PTCA medications
2. Compazine 3–5 mg slow i.v. push Q 4–6 hr; PRN for nausea
3. Morphine 3–5 mg i.v. 3–4 hr; PRN for pain
4. Valium 2–5 i.v. Q 6 hr; PRN for anxiety/restlessness
5. Dalmane 30 mg po Q HS PRN for sleep
6. KCL 20 meg/100 cc D5W over 2 hr PRN $K^+ < 3.7$ via central line
7. Transfuse 1 U RBCs for Hb 8.0 or less followed by post-transfusion Hb
8. Kefzol 1 g i.v. Q 8 hr × 2 days

MONITORING AND MISC.
1. V.S. Q 15 min × 1 hr, Q 30 min × 2 hr, then Q 1–2 hr
2. C.O. Q shift × 3
3. Measure thigh distal to CPS site on admission, then Q 4 hr × 3
4. When ACT < 240 sec after cannulae out, place C-clamp after 15 min of manual compression
5. Release C-clamp, after 90 min 2–3 mm Q 20 min as long as no oozing or bleeding is noted
6. Soft restraints to R&L ankle and knee strap on the bypass side
7. Check _____ pulse (RT)/(LT) by palpation or doppler
8. Accept capillary return (+)− if no pedal pulse prior to procedure
9. Silvadene 1% local cream with dressing at bypass site

HEPARIN STANDING ORDERS
Routine PCPS
1. Accept PTT 55–70. Increase heparin drip by *200* U/hr if PTT < 55
   If PTT is 71–100 reduce by *100* U/hr
   If PTT 101 or > hold heparin for 1 hr then resume by *200* U less

Emergent or acute PCPS only
2. Accept PTT 70–100. If PTT < 70 give *2000* U heparin bolus and increase heparin drip by 200 U/hr
3. Hold heparin drip only if any bleeding, and call MD

RECHECK PTT 1 HR AFTER ANY HEPARIN DRIP, BOTH ROUTINE AND ACUTE

PRE-PTCA MEDICATIONS
1.
2.
3.

procedure, or earlier in the event of recurrence of symptoms. In case of restenosis, repeat angioplasty using repeat cardiopulmonary bypass support was performed in most patients, unless the restenosis had occurred in only one vessel in a multivessel case. For repeat PCPS institution, either groin may be used.

All procedures were performed with a cardiac surgical team available for emergency bypass graft surgery, if appropriate. Informed consent was obtained in all patients.

RESULTS: CLINICAL CHARACTERISTICS (TABLES 7-4 TO 7-6)

Between April 1988 and February 1990, a total of 1932 coronary angioplasty procedures were performed at the Washington Adventist Hospital. Among

Table 7-4. Clinical characteristics of patients undergoing supported angioplasty

Total Patients	101 (69 M, 32 F)
Age	Range 41–86 years (mean 64)
Previous MI	93 (93%)
Cardiomyopathy	4 (3%)
Previous CHF	39 (39%)
Previous CABG	31 (31%)
Angina (CHC)	
Class III	43 (43%)
Class III	32 (32%)
Unstable	21 (21%)[1]
Recurrent pulmonary edema	5 (5%)

[1] 18 I/V NTG, 3 IAB support; NTG = nitroglycerin.
CHF = congestive heart failure; CABG = coronary artery bypass graft surgery; CHC = Canadian Cardiovascular Heart Class; MI = myocardial infarction.

Table 7-5. Associated diseases in patients undergoing supported angioplasty

Diabetes mellitus	24 (24%)
Previous CVA/TIA	15 (15%)
Severe COPD	13 (13%)
Renal failure	8 (8%)
Malignancy	6 (6%)
Crippling arthritis/osteoporosis	6 (6%)
On high-dose steroids	6 (6%)
Sternal dehiscence	5 (5%)

CVA = cerebrovascular accident; TIA = transient ischemic attack; COPD = chronic obstructive lung disease.

Table 7-6. Angiographic data before supported angioplasty in 101 patients

Number of epicardial coronary arteries with >50% stenosis:	
Left main	12[1]
Three vessel	92
Two vessel	6

[1] Unprotected left main in seven patients.

these procedures 101 (6%) patients underwent supported angioplasty. The majority of these patients were referred from other institutions (in the United States and abroad), specifically for cardiopulmonary bypass supported angioplasty. Supported angioplasty was undertaken as a substitute for coronary artery bypass graft surgery in 39 patients who were considered at high risk for coronary bypass graft surgery. Twenty-six were considered inoperable. All 36 patients were turned down for coronary bypass graft surgery by at least one cardiovascular surgeon and thus were deemed inoperable. Additionally, two patients had concomitant aortic valvuloplasty and one had deployment of an intracoronary stent in a venous graft.

There were 69 men and 32 women with an average age of 64 (range 41–86) years. A documented prior myocardial infarction was found in 93 patients (93%). In four patients (3%) a dilated cardiomyopathy of unknown cause was found. A prior history of congestive cardiac failure was noted in 39 patients (39%). Prior coronary artery bypass graft surgery had been performed in 31 patients (31%).

Severe angina (Canadian Cardiovascular Heart Class III or IV) was present in 75 patients (75%) and unstable angina in 21 patients (21%) (18 patients on intravenous nitroglycerin and three patients receiving intraaortic balloon counterpulsation). Five patients (5%) were in pulmonary edema at the time of the procedure. The majority of patients (52%) had an ejection fraction of $\leq$25%, including seven patients with an ejection fraction of <15%. Of 12 patients with critical left main stenosis, seven had no bypass grafts to the left coronary system. Of these seven patients, five were considered at a prohibitive risk for coronary bypass graft surgery and two had refused to undergo bypass surgery. In 86 patients (86%), at least one major coronary artery was totally occluded.

CARDIOPULMONARY BYPASS SUPPORT AND ANGIOPLASTY RESULTS (TABLE 7-7 AND 7-8)

With the institution of cardiopulmonary bypass support, filling pressures and systolic blood pressure declined in all patients. Administration of fluid through the pump was required in most patients (100–900 cc) to maintian adequate blood pressure during and before the termination of cardiopulmonary bypass support.

Pulmonary capillary wedge pressure (or pulmonary artery diastolic pressure) was $\leq$5 mmHg in 90% of patients. The mean diameter stenosis was reduced from 88% to 20%. The balloon was inflated for at least 3 minutes in most patients without subsequent enzymatic or electrocardiographic evidence of myocardial injury. Despite prolonged balloon inflation, only 20% of patients experienced angina. The average flow rate was 3.0 l/min, and the average bypass time was 37 minutes.

PTCA was attempted in 163 vessels (mean = $\pm$1.6 per patient). In 35 (35%), the only remaining patent vessel was dilated. Angioplasty was successful

Table 7-7. Results of 101 supported angioplasties

Angioplasty of iliofemoral vessels	2 (2%)
Flow rate during bypass	2.0–5.0 l/min (mean 3.1)
Chest pain during balloon dilatation	20 (20%)
ST-segment changes during balloon dilatation	23 (23%)
PAD or PCW $\leq$ 5 mmHg	90 (90%)
Total bypass time (minutes)	10–121
Mean bypass time	37

PAD = Pulmonary artery diastolic pressure; PCW = pulmonary capillary wedge pressure.

Table 7-8. Supported angioplasty data in 101 patients

Native	147
Vein graft/internal mammary	16
Total vessels attempted	163 (1.6/pt)
Dilatation of only remaining vessel	35 (35%)
Angiographic success rate	157/163 (97%)
Culprit vessel — success	101/101 (100%)
Prolonged inflation (>3 min)	101/101 (100%)[1]

[1] Culprit stenosis.

angiographically in 157 of the 163 vessels (97%), with the culprit vessel successfully dilated in all.

Two patients developed acute occlusion of a dilated vessel during the procedure, but both were redilated successfully using a larger balloon and prolonged inflation. In one of these patients, a 10-minute balloon inflation was performed and in another, intracoronary tissue plasminogen activator was administered in addition to repeat dilatation without any subsequent evidence of myocardial infarction (by creatinine kinase MB determination or electrocardiographic changes).

COMPLICATIONS

No patient required emergency coronary bypass graft surgery. All patients left the cardiac catheterization laboratory without any mechanical support.

The complications due to PCPS were mostly at the bypass cannulae insertion site (Table 7-9), and none were life threatening. These local complications occurred only in patients in whom the cannulae were removed in the catheterization laboratory shortly after the completion of the PTCA procedure. Since these patients had a large amount of circulating heparin still present, hemostasis required prolonged clamping (average clamp compression of 12 hours).

Currently, the cannulae are left in place until the activated clotting time has dropped to less than 240 seconds. Using this cannulae removal technique, no local complicaitons were encountered in the last 31 patients. Also, with the

Table 7-9. Complications[1] encountered during 101 supported angioplasty procedures

Number of complications	
Complications Requiring Local Surgery	
Pseudoaneurysm	4
Enlarging hematoma (repair femoral artery)	2
Infection requiring debridement	2
Embolus to popliteal artery	1
Arteriovenous fistula	1
TOTAL	10 (10%)[1]
Other Complications	
Femoral nerve weakness	4[2]
Minor superficial skin infection	5
Superficial skin abrasion/necrosis	4[2]
Minor gastrointestinal bleed	1
Deep venous thrombosis	1
Transient ischemic attack 48 hours postprocedure	1
Air embolus	1
Diabetic ketoacidosis	1
TOTAL	18

[1] No complications using current cannulae removal technique.
[2] Due to clamp (early experience), more than one complication in the same patient. None with the current technique.

new cannula removal technique, maximum clamp compression was necessary for only a mean of 1.5 hours.

The most common complication was the need for a blood transfusion. In the first 78 patients in whom the previous cannulae removal technique was used, 25 patients required blood transfusion, while in the last 21 patients in whom the current cannulae removal technique was used, none required blood transfusion.

In our initial experience, one patient was noted to have air in the right ventricular outflow tract just after the Swan Ganz catheter was introduced through the subclavian vein. The air from the right ventricular outflow tract was successfully evacuated using the Swan Ganz catheter with no sequelae. The source of entry was most likely through the subclavian entry. From this patient, one learns not to enter any venous site while the patient is on cardiopulmonary bypass.

One patient, with known history of carotid artery disease, developed a transient ischemic attack 48 hours after supported angioplasty. It is likely that this complication was unrelated to the supported intervention. Femoral nerve weakness, noted in our initial experience, was eliminated using the current cannulae removal protocol because of short clamp compression for hemostasis and the development of a new compression disc.

One patient developed an acute occlusion in one of the two vessels dilated 24 hours after the procedure following discontinuation of heparin. Because of hypotension, an intraaortic balloon pump was inserted, and the patient was treated with tissue plasminogen activator and repeat coronary angioplasty.

This patient, however, did sustain a non-Q-wave myocardial infarction and required surgical repair of the femoral artery.

Another patient developed an acute occlusion of the left circumflex 5 days after angioplasty. This was one of two vessels initially dilated. Redilation was performed with only a small elevation of creatinine kinase MB.

There were three in-hospital deaths. No death was related to the institution of cardiopulmonary bypass support. The first death was in a patient who was a 70-year-old woman who developed an acute occlusion of the right coronary artery 4 days after multivessel coronary angioplasty. Despite successful repeat dilation, she died 9 days later due to renal failure, congestive heart failure, and gastrointestinal bleeding. This patient had also initially undergone angioplasty of the left main and left circumflex, and both were patent at the time of study.

The second patient was a 76-year-old man with multiple medical problems, which included cerebrovascular accident, chronic obstructive lung disease, and chronic renal failure. He had been deemed inoperable. This patient developed respiratory arrest due to aspiration 10 days after the procedure.

The third patient was a 67-year-old man with an ejection fraction of 30% who died suddenly on the day of discharge due to ventricular fibrillation.

FOLLOW-UP

The follow-up (6–19 months, mean 12) data were obtained in all 98 discharged patients (Table 7-10). A symptomatic recurrence was noted in 26 patients (26%), due to restenosis in 24, and due to a new lesion in two. Of these 26 patients, 16 underwent repeat angioplasty. In these 16 patients, repeat PCPS was instituted in eight (in two patients balloon inflation without support produced severe chest pain and hypotension), and in the remaining eight, PTCA was performed without support, since not all the lesions initially dilated recurred. Also, these eight patients were minimally symptomatic and

Table 7-10. Clinical status and follow-up in 98 patients discharged alive

Recurrent symptoms		26 (27%)
Restenosis		24 (25%)
New lesions		2 (3%)
Repeat PTCA		16 (17%)[1]
CABG		8 (9%)
Medical therapy		2 (3%)
Late deaths		
Cardiac		8 (9%)[2]
Noncardiac		1 (2%)
Survivors		89/98 (90%)
Asymptomatic	Class I	79 (88%)
	Class II	8 (9%)
	Class III	2 (3%)

[1] Eight repeat PCPS.
[2] Three following elective bypass surgery for restenosis in patients initially deemed inoperable.

improved left ventricular function was noted in four. In two patients new lesions were dilated.

In eight patients, elective bypass graft surgery was performed. Of these eight, three who were initially deemed inoperable underwent bypass surgery at another institution, and all three died. Two patients who were initially deemed high risk for bypass surgery underwent coronary bypass graft surgery. Both had a long hospital course (mean = 3 weeks). Three patients who had initially undergone supported PTCA as a substitute for surgery had restenosis of the left main coronary artery. These patients underwent successful coronary bypass graft surgery without any complications.

There were nine late deaths (9%), with eight ascribed on the death certificate to coronary artery disease. One patient died following noncardiac surgery. At a mean follow-up of 12 months, there were, thus, a total of 12 deaths (three in-hospital and nine late death). Therefore the survival rate was 89%. Of these 89 patients, 79 (90%) were asymptomatic or Class I, eight (9%) were Class II, and the remaining two (2%) were Class III.

Other complications noted during the follow-up are listed in Table 7-9. Of the four patients with femoral nerve weakness (all of these patients had the previous removal technique), three have completely recovered, while one still requires a cane to assist in walking. The last 31 patients, who underwent supported PTCA using the current cannulae removal method, demonstrated no local complications during follow-up (including no venous thrombosis or pseudoaneurysm formation).

COMMENTS

Because of advances in technology, it is possible to intervene in patients who were previously at a prohibitively "high risk" for PTCA or CABG. This "high risk" group includes patients with poor left ventricular function, prior bypass surgery, advanced age, and those with severe associated illnesses, e.g., severe obstructive lung disease, renal insufficiency, etc.

Coronary bypass surgery in this group of patients carries a high operative risk [34,35]. Previous surgical series had an operative mortality of 13–27% [36–38]. More recent studies, using improved operative techniques and patient selection, report a reduced mortality of approximately 8% [35,39,40].

Although PTCA is associated with a high success rate in carefully selected patients, abrupt closure, which cannot be predicted beforehand, [8], occurs in approximately 5% of patients [8,9] and can result in hemodynamic collapse or death [10]. Few reports are available on the use of PTCA in this high risk group. Major complications (myocardial infarction, death, and emergency coronary bypass surgery) resulting from elective unsupported PTCA in patients with an ejection fraction of 35–40% has been reported to be 5%, with a mortality in the catherization laboratory of 3% [22,41]. Lewin et al. [42] reported higher mortality in patients with an ejection fraction of <35% and prior coronary bypass graft surgery.

In order to perform PTCA in these "high risk" patients, some form of circulatory support is necessary, not only to stabilize the patient in the event of abrupt closure, but also to avoid hemodynamic compromise during balloon dilatation. We and others [25,30–33] have reported the prohylactic use of PCPS during "high risk" coronary angioplasty. In these reports, PTCA was performed not only in patients considered at "high risk," but also in patients deemed inoperable. Despite the lack of coronary perfusion during prolonged balloon dilatation during supported PTCA, these patients tolerated the procedure well. Chest pain or ischemic electrocardiographic changes were noted in less than 23%. The very low pulmonary artery pressures, as well as elimination of chest pain by increasing the flow rate, suggest unloading rather than collateral flow as the likely explanation for the lack of chest pain or ischemic electrocardiographic changes during balloon inflation.

In our series, no patient died or sustained a myocardial infarction during the procedure, and none required emergency bypass surgery. The current hospital mortality of 3% compares very favorably with the approximately 7% mortality in patients undergoing coronary bypass graft surgery with ejection fractions of <35%. However, no data exist with which to compare very low morbitity and mortality in our series of supported angioplasties who were deemed surgically inoperable and those in whom the only patent vessel was dilated.

Early closure and late restenosis may be a limiting factor in using percutaneous cardiopulmonary bypass support in these high risk patients. In our first 101 patients, three (3%) developed acute closure 24 hours after the procedure. One died despite successful repeat dilatation, and two other patients, who had undergone multivessel dilatation, were successfully redilated without bypass support, which was possible because not all vessels initially dilated had closed. One of these patients did require an intraaortic balloon pump. However, if abrupt closure had occurred in patients whose only remaining vessel was dilated, severe hemodynamic compromise would have occurred.

The long-term outcome in patients with poor left ventricular function and improved coronary perfusion following coronary angioplasty remains to be determined. Results from the CASS study [40] indicate a more favorable survival pattern and should, therefore, closely correlate with the extent of revascularization achieved. Although the clinical follow-up is short (average 12 months), the clinical improvement is encouraging, with 88% of patients asymptomatic or Class I, and 12% in Class II or III. The clinical restenosis rate in this series was 25%. However, the actual restenosis rate cannot be assessed, because not all patients have undergone repeat angiography. Also, the survival rate of 90% at a mean follow-up of 12 months is encouraging.

Others have reported the use of cardiopulmonary bypass to support high risk PTCA patients [25,31,43–45]. Taub et al. [43] reported seven patients who underwent cardiopulmonary bypass supported PTCA. Six had surgical placement and in one bypass cannulae were placed percutaneously. Of the

seven, six developed groin hematomas, four developed deep venous thrombosis, and one patient had arterial occlusion. Six patients survived and one died after retroperitoneal hemorrhage. In addition to being cumbersome in the catheterization laboratory, the authors suggested that surgical placement of cannulae is associated with a substantial morbidity.

A national registry of supported angioplasty has reported its results [31]. Fourteen centers throughout the United Stated performed supported PTCA in 105 patients. Twenty patients had inoperable coronary artery disease, 30 had dilatation of their only remaining patent vessel, and 17 had dilatation of their left main coronary artery. During this study, the authors found that percutaneous insertion gradually replaced surgical cutdown for cannulae insertion. The angioplasty success rate was 95%. Forty-one patients had significant morbidity, mostly in the form of arterial, neurological, or venous injury due to cannulae placement. The high morbidity found in this study has been markedly reduced (to <15%) in newer registry data because of increased use of the percutaneous technique, as well as improvement in the cannulae removal technique. The author believes that use of the technique described in Chapter 6 will result in further reduction of morbidity.

OTHER SUPPORT DEVICES

With the other support devices, use of the intraaortic balloon pump to support high risk PTCA patients has been reported [28,29]. In some patients this may provide adequate support. However, in patients who cease to have an effective cardiac rhythm, the intraaortic balloon pump is ineffective. Also, the cirulatory support provided is limited, and patients with sufficiently severe hemodynamic compromise will not benefit.

The role of the hemopump and the autoperfusion and retroperfusion catheters is discussed elsewhere in this book.

MANAGEMENT OF ABRUPT CLOSURE

Abrupt closure can occur either inside the cardiac catheterization laboratory during the course of supported angioplasty or outside the catheterization laboratory following the procedure. This difference may be important, since patients who have abrupt closure inside the catheterization laboratory are in a relatively controlled environment. If a patient is still on bypass, repeat coronary angiography can be performed and the site of occlusion identified. Then, an attempt is made to cross the lesion, and dilatation is performed with prolonged inflation using low pressure and a balloon size that is slightly larger than the target vessel. Following dilatation, the patient is observed in the catheterization laboratory for at least 30 minutes. If repeat angiography shows continued good results with no major dissection, the patient can be transported to the coronary care unit. The patient should be intensely anticoagulated. As an added safety measure, cardiopulmonary bypass cannulae can be left in place for up to 24 hours and the CPS pump left at the bedside primed. If

repeat dilatation is unsuccessful, stent placement, laser balloon angioplasty, and coronary bypass graft surgery must be considered. Abrupt closure outside the catheterization laboratory is heralded by the sudden onset of chest pain, ischemic electrocardiographic changes, or both. Hypotension usually ensues and cardiac arrest is common. Patients with acute closure of only one of the several vessels dilated may remain stable. The initial approach depends upon the degree of hemodynamic compromise following abrupt closure. In case of hypotension, cardiopulmonary bypass support can be instituted at the bedside, since bypass cannulae are still in place. After stabilization, the patient is transported to the catheterization laboratory and treated as decribed above.

If bypass cannulae have already been removed, cardiopulmonary bypass support can be instituted from the contralateral groin. Nonetheless, it is in this group of patients that mortality will be high, particularly if the only remaining patent vessel is occluded.

In view of the risk of abrupt closure, one should avoid dilating lesions (diffuse, tortuous, angulated), which are at high risk for abrupt closure, and dissection [46], particularly if the patient is inoperable.

CONCLUSION

The development of percutaneous cardiopulmonary support provides an additional technique to support patients undergoing high risk coronary angioplasty in the cardiac catheterization laboratory. Our initial results do suggest that supported angioplasty can be successful in high risk patients, with an acceptable morbidity and mortality. Local complications due to cannulae insertion have been virtually eliminated using the current removal technique. The hemodynamic stability achieved during supported angioplasty not only permits PTCA to be performed in such high risk patients, but it also reduces the operator's anxiety about arrhythmia and hemodynamic instability. Also, in the event of abrupt closure during supported angioplasty, emergency surgical revascularization, repeat dilation, or even stent placement or laser balloon angioplasty can be performed safely. Since PCPS does produce substantial unloading of the left ventricle, the risk of myocardial infarction may be minimized. Nonetheless, echocardiographic data demonstrate that ischemia does occur during balloon inflation, in spite of the unloading that occurs. This indicates that PCPS may not prevent myocardial infarction if the artery remains occluded for a protracted period. Perfusion of myocardium distal to the occlusion, using a separate perfusion system, is under investigation and may be beneficial.

REFERENCES

1. Gruentzig AR. Transluminal dilatation of coronary artery stenoses. *Lancet* 1978; 1:263.
2. Gruentzig AR. Senning A, Siegenthaler WE. Non-operative dilatation of coronary artery stenosis: Percutaneous transluminal coronary angioplasty. *N Engl J Med* 1979; 301:61–68.
3. Cowley MJ, Vetrovec GW, Wolfgang TC. Efficacy of percutaneous transluminal coronary

angioplasty: Technique, patient selection, salutory results, limitations and complications. *Am Heart J* 1981; 101:272–80.
4. Cowely MJ, Vetrovec GW, DiSciascio G, Lewis SA, Hirsch PA, Wolfgang TC. Coronary angioplasty of multiple vessels: Short-term outcome and long-term results. *Circulation* 1985; 72:1314–1320.
5. Dorros G, Stertzer SH, Cowley MJ, Myler RK. Complex coronary angioplasty: Multiple coronary dilatations. *Am J Cardiol* 1984; 53:126C–130C.
6. Quigley PJ, Erwin J, Maurer BJ, Walsh MJ, Gearty GF. Percutaneous transluminal coronary angioplasty in unstable angina: Comparison with stable angina. *Br Heart J* 1986; 55:227–230.
7. Faxon DP, Detre KM McCabe CH, Fisher L, Holmes DR, Cowley MJ, Bourassa MG, VanRaden M, Ryan TJ. Role of percutaneous transluminal coronary angioplasty in the treatment of unstable angina: Report from the National Heart, Lung and Blood Institute Percutaneous Transluminal Coronary Angioplasty and Coronary Artery Surgery Study Registries. *Am J Cardiol* 1984; 53(Suppl. C):131–135.
8. Cowley MJ, Dorros G, Kelsey SF, VanRaden M, Detre KM. Acute coronary events associated with percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1984; 53:12C–16C.
9. Bredlau C, Roubin GS, Leimgruber PP, Douglas JS Jr., King SB III, Gruentzig AR. In-hospital morbidity and mortality in patients undergoing elective coronary angioplasty. *Circulation* 1985; 72:1044–1052.
10. Dorros G, Cowley MJ, Janke L, Kelsey SF, Mullin SM, VanRaden M. In-hospital mortality rate in the National Heart, Lung, and Blood Institute Percutaneous Transluminal Coronary Angioplasty Registry. *Am J Cardiol* 1984; 53:17C–21C.
11. Talley JD, Weintraub WS, Anderson HV, Jones EL, King SB, Douglas JS, Murphy DA, Craver JM Liberman HA, Morris DC, Guyton RA, Hatcher CR. Late clinical outcome of coronary bypass surgery after failed PTCA (abstr) *Circulation* 1987; 76:IV–352.
12. Parsonet V, Gielchinsky I, Hochberg MS, Hussain SM, Fisch D, Rothfield L. Emergency surgery after failed angioplasty (abstr). *Circulation* 1987; 76:IV–352.
13. Roubin GS, Talley JD, Anderson HV, Murphy DA, Guyton RA, Jones EL, Craver JM, Lembon, Douglas JS, King SB III. Morbidity and mortality associated with emergency bypass graft surgery following elective coronary angioplasty (abstr). *J Am Coll Cardiol* 1987; 9:124A.
14. Sigwart U, Puel J, Mirkovitch V, Jaffre F, Kappenberger L. Intravascular stents to prevent occlusion and restenosis after transluminal angioplasty. *N Engl J Med* 1987; 316:701–706.
15. Jenkins RD, Spears JR. Laser balloon angioplasty: A new approach to abrupt coronary occlusion and long-term restenosis. *Circulation* 1990; 81(Suppl. IV):IV-101–108.
16. Ellis SG, Roubin GS, King SB III, et al. In-hospital cardiac mortality after acute closure after coronary angioplasty: Analysis of risk fators from 8207 procedures. *J Am Coll Cardiol* 1988; 11:211–216.
17. Park DD, Laranice LA, Tierstein P, et al. Major complications during PTCA: An analysis of 5413 cases. *J Am Coll Cardiol* 1988; 11:237A.
18. Harnarayan C, Bennett MA, Pentecost BL, Brewer DB. Quantitative study of infarcted myocardium in cardiogenic shock. *Br Heart J* 1970; 32:728–732.
19. Siguemituzo A, Cheechi H, Coelho WM, Bellotti G, Pileggi F. Coronary angioplasty: Unstable lesions and prolonged balloon inflation time. *Cathet Cardiovasc Diag* 1990; 19:77–83.
20. Hartler GO. Complex coronary angioplasty: An alternative therapy. *Int J Cardiol* 1985; 9:133–137.
21. Detre K, Holobkov R, Kelsey S, et al. Percutaneous transluminal coronary angioplasty in 1985–1986 and 1977–1981. The National Heart, Lung, and Blood Institute Registry. *N Engl J Med* 1988; 318:265–270.
22. Harzler GO, Rutherford BD, McConahay DR, Johnson WL, Giorgi LV. "High risk" percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1988; 61:33G–37G.
23. O'Keefe JH Jr., Hartzler GO, Rutherford BD, et al. Left main coronary angioplasty: Early and late results of 127 acute and elective procedures. *Am J Cardiol* 1989; 64:144–147.
24. Zalewski A, Goldberg S. Protection of the ischemic myocardium during coronary angioplasty. In: Goldberg S, ed, *Coronary Angioplasty*. F.A. Davis, New York 1988, pp. 79–98.
25. Vogel RA, Tommaso CL, Gundry SR. Initial experience with coronary angioplasty and aortic valvuloplasty using elective semipercutaneous cardiopulmonary support. *Am J Cardiol* 1988: 62:811–813.

26. McDonald RG, Hill JA, Feldman RL. Failure of intra-aortic balloon counterpulsations to augment distal coronary perfusion pressure during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1987; 59:359–361.
27. Szatmary LJ, Marco J, Fajadet J, Caster L. The combined use of diastolic counterpulsation and coronary dilatating in unstable angina due to multivessel disease under unstable hemodynamic conditions. *Int J Cardiol* 1988; 19:56–66.
28. Voudris V, Marco J, Morice MC, Fajadlt J, Royer T. "High risk" percutaneous transluminal coronary angioplasty with preventive intra-aortic balloon counterpulsation. *Cathet Cardiovas Diag* 1990; 19:160–164.
29. Kahn JK, Rutherford BD, McConahay DR, et al. Supported "high risk" coronary angioplasty using intraaortic balloon pump counterpulsation. *J Am Coll Cardiol* 1990; 15:1151–1155.
30. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Percutaneous cardiopulmonary bypass support in high-risk patients undergoing percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1989; 64:1258–1263.
31. Vogel RA, Shawl FA, Tommaso C, O'Neill W, Overlie P, O'Toole J, Vandormael M, Topol W, et al. Initial report of the national registry of elective cardiopulmonary bypass supported angioplasty. *J Am Coll Cardiol* 1990; 15:23–29.
32. Shawl FA. Percutaneous cardiopulmonary bypass support in high risk coronary angioplasty. *Cardiol Clin* 1989; 87(4):865–875.
33. Shawl FA. Percutaneous cardiopulmonary bypass support in high risk interventions. *J Invas Cardiol* 1989; 5:287–293.
34. Kuan P, Burnstein SB, Ellestead MH. Coronary artery bypass surgery morbidity. *J Am Coll Cardiol* 1984; 3:1391–1397.
35. Kennedy JW, Kaiser GC, Fisher LD, et al. Clinical and angiographic predictors of operative mortality from the collaborative study in coronary artery surgery (CASS). *Circulation* 1981; 63:793–802.
36. Sheldon W, Ricon G, Pichard AD, et al. Surgical treatment of coronary artery disease: Pure graft operation, with a study of 741 patients followed 3 to 7 years. *Prog Cardiovasc Dis* 1985; 28:237.
37. Lubiate P, Kraj JH, Mendez AM. Myocardial revascularization for the treatment with drastic impairment of function of the left ventricle. *J Thorac Cardiovasc Surg* 1977; 44:73–84.
38. Hochberg MS, Parsonnet V, Gielchinsky I, et al. Coronary artery bypass grafting in patients with ejection fraction below 40. *J Thorac Cardiovasc Surg* 1983; 85:519.
39. Shearn DL, Brent BN. Coronary artery bypass surgery in patients with poor left ventricular function. *Am J Med* 1986; 80:405.
40. Alderman EL, Fisher LD, Litwin P, Kaiser GL, Myeri, Maynard C, Levine F, Scholass M. Results of coronary artery surgery in patients with poor left ventricular function (CASS). *Circulation* 1983; 68:785–795.
41. Kohli RS, Verovec GW, Disciassia G, Lewis SA, Nath A, Cowley MJ. Coronary angioplasty in patients with severe depression of left ventricular function. *J Am Coll Cardiol* 1989; 13: 222A.
42. Lewin RF, Dorros G. Percutaneous transluminal coronary angioplasty in patients with severe left ventricular dysfunction. *Cardiol Clin* 1989; 4:813–825.
43. Taun JO, Lhommedieu BD, Raithel, et al. Extracorporeal membrane oxygenator for percutaneous coronary angioplasty in high risk patients. *ASAIO Trans* 1989; 35(3):664–666.
44. Freedmann RJ Jr., Wrem RC, Godley ML, et al. Complex multiple percutaneous transluminal coronary angioplasties with vortex oxygenator cardiopulmonary support in the community hospital setting. *Cathet Cardiovasc Diag* 1989; 17(4):237–242.
45. Vogel JH, Ruiz CE, Jahnke EJ, et al. Percutaneous (non-surgical) supported angioplasty in unprotected left main disease and severe left ventricular dysfunction. *Clin Cardiol* 1989; 12(5):297–300.
46. Ryan J, et al. Guidelines for percutaneous transluminal coronary angioplasty. *J Am Coll Cardiol* 1988; 12:529.

8. EMERGENCY INSTITUTION OF CARDIOPULMONARY BYPASS SUPPORT IN CARDIOGENIC SHOCK

MICHAEL J. DOMANSKI AND FAYAZ A. SHAWL

INTRODUCTION

Cardiogenic shock occurs when the heart cannot pump sufficient blood to meet the metabolic demands of the body [1]. The shock state may be identified clinically by the presence of a systolic blood pressure <80 mmHg associated with signs of hypoperfusion, including oliguria, impaired mental status, and cool skin [2,3]. This is accompanied by a cardiac index <1.8 l/min/m^2 in the presence of a left ventricular filling pressure >18 mmHg [3].

Cardiogenic shock occurs in 5–15% of patients with acute myocardial infarction [4–8], most commonly in patients with anterior infarction and in those who have had a previous myocardial infarction [9]. The prognosis with conventional therapy is poor, with a mortality rate that may exceed 85% [10–12].

Cardiogenic shock may also be caused by mechanical complications of acute myocardial infarction, such as ventricular septal defect, mitral valve dysfunction, or rupture of the ventricle [2]. Most often, however, it is due to ischemic dysfunction of >40% of the myocardium [1,13,14]. While cardiogenic shock may be present on admission [15], the more usual situation is for the patient to present in a stable condition, only to have shock evolve as the hospitalization progresses [16,17].

Recognition of the development of the clinical manifestations of cardiogenic shock is essential if treatment is to be instituted in a timely fashion. Placement of a pulmonary artery catheter to confirm the diagnosis and to guide therapy

is essential. When hypotension and low cardiac output are secondary to volume depletion, rather than to the syndrome described above, plasma volume expansion is indicated.

Data have accumulated suggesting that rapid restoration of blood flow to the ischemic myocardium by coronary artery bypass graft surgery (CABG) or by percutaneous transluminal coronary angioplasty (PTCA) may improve survival in these patients. In order to perform angioplasty, the patient must be sufficiently stable for angiography and subsequent intervention. The use of intraaortic balloon counterpulsation has been reported in this setting [18] but is not useful in patients without an intrinsic rhythm or in those in whom left ventricular failure is sufficiently severe. Cardiopulmonary bypass support, on the other hand, can maintain hemodynamic stability, even in the absence of cardiac function [19–22], facilitating PTCA, which may improve survival. The role of percutaneous cardiopulmonary bypass support (PCPS) in the management of patients with cardiogenic shock is the subject of this chapter.

PATIENT SELECTION

Patient are selected for PCPS if they have a systolic blood pressure of $\leq$80 mmHg on inotropes and/or intraaortic balloon counterpulsation and evidence of hypoperfusion (including compromised sensorium, poor urinary output, and cool extremities). Patients are excluded if the duration of cardiogenic shock is >4 hours (unless there is evidence of ongoing ischemia) or if they have a history of symptomatic peripheral vascular disease. Also, patients with a history of bleeding diathesis are excluded.

TECHNIQUE OF PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT

A detailed description of the technique of PCPS is provided by Shawl in Chapter 6. The technique that is recommended for such patients by the authors is briefly described below.

The patient is taken to the catheterization laboratory, where 8 Fr sheaths are inserted in both groins. Iliofemoral angiography is performed unless the patient is in cardiac arrest. Following placement of a pulmonary artery catheter (except in cardiac arrest), the patient is heparinized with 250–300 U/kg of body weight to achieve an activated clotting time of $\geq$400 seconds. A 0.038-in. flexible J-tip guidewire is inserted through the 8 Fr arterial sheath, which is then exchanged for a long 8 Fr dilator. The 0.038-in. flexible J-tip guidewire is then replaced by a stiff 0.038-in. guidewire. The dilator is removed over this wire, and sequential dilatations are carried out with a 12 Fr, followed by a 14 Fr, dilator. Then, an 18 Fr arterial cannula is placed in the artery over the stiff guidewire, which is withdrawn, and the cannula is then clamped. Using a similar technique, an 18 Fr venous cannula is introduced and then the tip is positioned just above the junction of the inferior vena cava and right atrium. In patients who are already on an intraaortic balloon pump with compromised

hemodynamics, the balloon pump is removed as one unit over the 0.035-in., extra-stiff guidewire (U.S.C.I., Billerica, MA), and an 18 Fr arterial cannula is directly introduced without any further dilatation.

Initiation of cardiopulmonary bypass support

Following placement, cannulae are attached to the bypass pump and flow is initiated using 50–60 ml/kg of body weight or 2.2–2.7 l/min. Once hemodynamic stability is achieved, all inotropic agents are discontinued. Angiography is performed next, followed by angioplasty, if feasible.

CORONARY INTERVENTION

After the patient is stabilized, the angiogram is reviewed and a decision is made about the most appropriate intervention (PTCA or CABG). When PTCA is feasible, the culprit vessel is dilated first. If there is an excellent result, then other non-infarct-related vessels are dilated if they appear amenable to PTCA. If the lesions in these vessels are considered to present a high risk of complication, PTCA is postponed or CABG is recommended (emergently if necessary). When angiography discloses anatomy not amenable to PTCA, the patient is transferred, on PCPS, to the operating room for urgent CABG.

TERMINATION OF SUPPORT

Once a good angiographic result is obtained, weaning the patient off bypass can begin. A reduction in bypass flow may result in a drop in systemic pressure, making gradual weaning necessary. In some cases, inotropes and/or placement of an intraaortic balloon pump may be necessary. In an unstable patient where bypass may have to be reinstituted, cannulae can be left in place for up to 24 hours, as long as the patient is adequately anticoagulated.

Patients who cannot be weaned from PCPS in the catheterization laboratory can be weaned after transfer to the coronary care unit. Sometimes these patients will experience a rise in their left ventricular filling pressure and a drop in systemic blood pressure as bypass flow is reduced. In such cases, gradual weaning (0.5 l/min every 30–60 minutes) is performed and inotropes and an intraaortic balloon pump (using the PTCA access) are added as needed.

After the termination of cardiopulmonary bypass, autotransfusion of blood remaining in the bypass system is performed. Cannulae are left in place until the activated partial thromboplastin time has dropped to <240 seconds. Heparin is restarted after the activated clotting time has fallen to <200 seconds or the partial thromboplastin time is <80 seconds.

RESULTS

We have previously reported on eight patients, 42–80 years of age [23] (Tables 8-1 to 8-3), in whom PCPS was instituted early in the setting of cardiogenic shock due to acute myocardial infarction. Two of the eight were in cardiac arrest prior to the initiation of cardiopulmonary bypass, one had severe mitral

Table 8-1. Clinical and angiographic characters of patients

Case	Age	Acute MI	Prior MI	EF%	Number of diseased vessels	Infarct-related artery
1	68	Lateral	Anterior Inferior	28	3	LCX
2	52	Anterior	None	31	1	LAD
3	61	Anterior	None	40	2	LAD
4	62	Inferior	Lateral	38	2	RCA
5	65	Inferior	None	30	1	RCA
6	80	Inferior	Anterior	17	3	RCA
7	69	Inferior	None	35	1	RCA
8	42	Anterior	Inferior	28	1	LAD

EF = ejection fraction; LAD = left anterior descending; LCX = left circumflex; IRA = infarct-related artery; MI = myocardial infarction.

Table 8-2. Cardiopulmonary bypass support: Flow rate and bypass duration

Case	Shock to bypass (minutes)	Maximum flow rate (l/min)	Bypass time (min)
1	45	3.5	44
2	90	3.6	52
3	65	3.4	48
4	180	3.2	45
5	180	3.7	67
6	30	5.2	120
7	170	5.0	90
8	150	4.5	62

Table 8-3. Hemodynamic data

	Pre bypass			On bypass			Postbypass		
Case	MBP (mmHg)	PA (mmHg)	PCW (mmHg)	MBP (mmHg)	PA (mmHg)	PCW (mmHg)	MBP (mmHg)	PA (mmHg)	PCW (mmHg)
1	54	50/28	26	70	12/0	0	73	48/20	16
2	38	36/22	20	76	6/0	0	60	21/12	12
3	46	34/20	20	68	5/0	0	58	26/14	14
4	44	18/11	10	68	4/0	0	72	28/12	12
5	55	50/28	28	70	7/2	2	102	30/26	15
6	Cardiac arrest			72	6/3	2	Expired		
7	Cardiac arrest			70	7/3	2	75	26/10	10
8	47	56/24	22	65	5/0	0	76	30/15	15

MBP = mean blood pressure; PA = pulmonary artery pressure; PCW = pulmonary capillary wedge pressure.

regurgitation, and all were in pulmonary edema, with the exception of one patient who had a right ventricular infarction. Cardiogenic shock was of ≤4 hours duration in all patients, and chest pain in these patients was of 2–7 hours duration. The average time from the onset of shock to the initiation of cardiopulmonary bypass was 106 minutes. All patients were placed on cardiopulmonary bypass in the catheterization laboratory. Prior to the initiation of bypass, one patient was on an intraaortic balloon pump and all were on inotropic support.

The adequacy of cardiopulmonary bypass support is demonstrated by the hemodynamic profile on bypass and is also suggested by the fact that the two patients who were in cardiac arrest awoke in the absence of effective cardiac function. In this series, all of the infarct-related vessels were successfully dilated and dilatation was attempted in other critically stenosed arteries. In all, 15 of 16 lesions attempted were successfully opened. Neither PTCA nor coronary bypass surgery was possible in one patient who expired. The other seven patients, who were successfully dilated, survived and are still alive more than a year after dilatation. It is of interest that none of the patients left the catheterization laboratory on a mechnical circulatory support device, suggesting a rapid, substantial recovery of myocardial function after dilatation.

It is important to note that the patients in this series were treated within 4 hours of the onset of cardiogenic shock. Later treatment may have been less effective.

COMPLICATIONS

Most of the patients in this series required transfusion. This reflects early experience with the technique and, based on experience in the elective group, would probably be far less frequent now because of the current practice of allowing the activated partial thromboplastin time to fall below 240 seconds before catheter removal and because of a recognition that much of the fall in hemoglobin that occurs early following bypass is secondary to hemodilution. The necessity for femoral artery repair following bypass was infrequent.

CASE EXAMPLE

This is a case of cardiogenic shock in a patient with three-vessel coronary disease. A 70-year-old woman with an inferior myocardial infarction received intravenous thrombolysis with clinical evidence of reperfusion. Forty-eight hours later she developed chest pain, marked inferior and anterior ST elevations (Figure 8-1A), and cardiogenic shock (despite large doses of inotropes). She was taken to the catheterization laboratory within 2 hours of the onset of shock, where a Swan-Ganz catheter placed via the right femoral vein revealed a pulmonary capillary wedge pressure of 22 mmHg. A left iliofemoral angiogram (Figure 8-2) showed a widely patent left femoral artery. The patient was placed on PCPS with a decrease in the pulmonary capillary wedge pressure to 10 mmHg, an increase in the systemic blood pressure, and an improvement

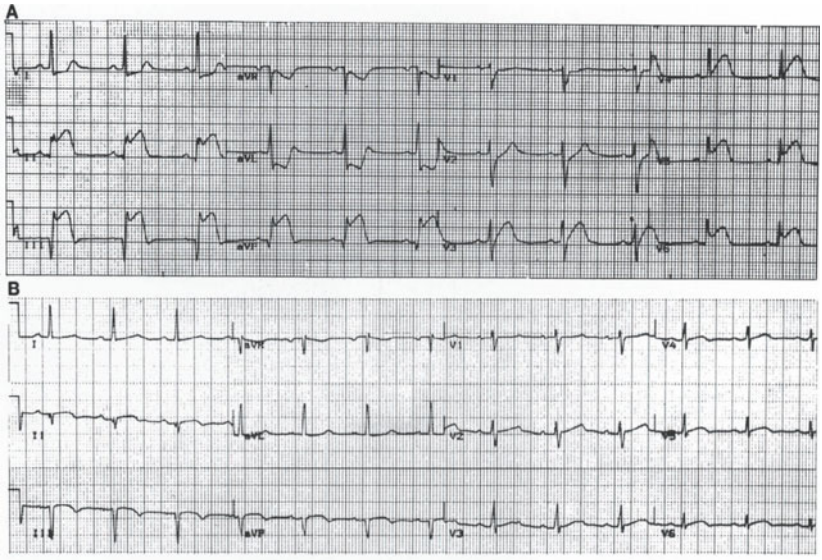

Figure 8-1. *A*: 12-lead electrocardiogram showing inferior and anterior ST-segment elevations prior to emergency institution of PCPS. *B*: Repeat electrocardiogram after successful multivessel PTCA and uneventful weaning from bypass support.

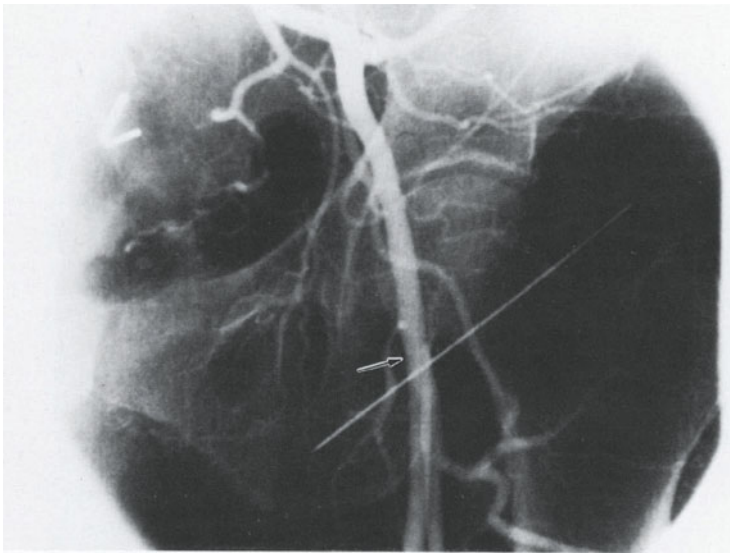

Figure 8-2. Angiogram of left iliofemoral system (prior to bypass cannula placement) showing left common (arrow) femoral artery of adequate caliber for cannulation for PCPS.

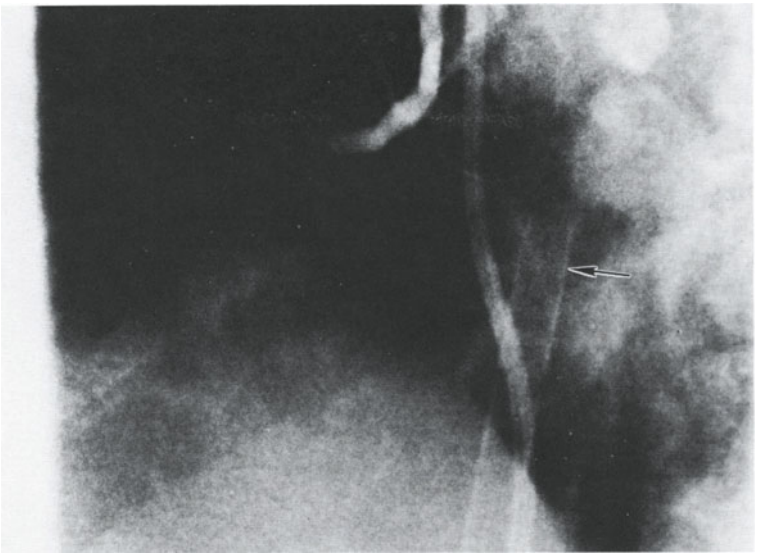

Figure 8-3. Coronary angiogram performed after achieving hemodynamic stability on PCPS, showing a totally occluded right coronary artery. Note the position of the venous bypass cannula in the right atrium (arrow).

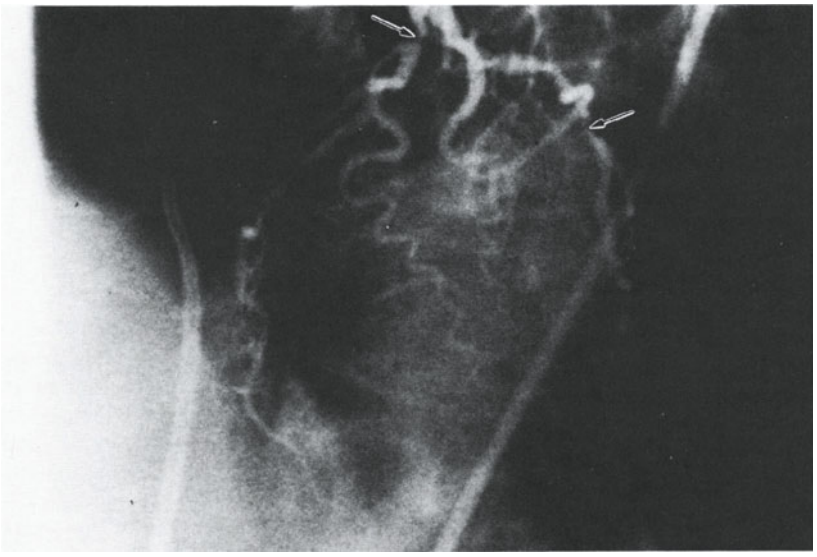

Figure 8-4. Coronary angiogram showing critical stenoses (arrows) of the proximal left anterior descending coronary artery and the mid left circumflex.

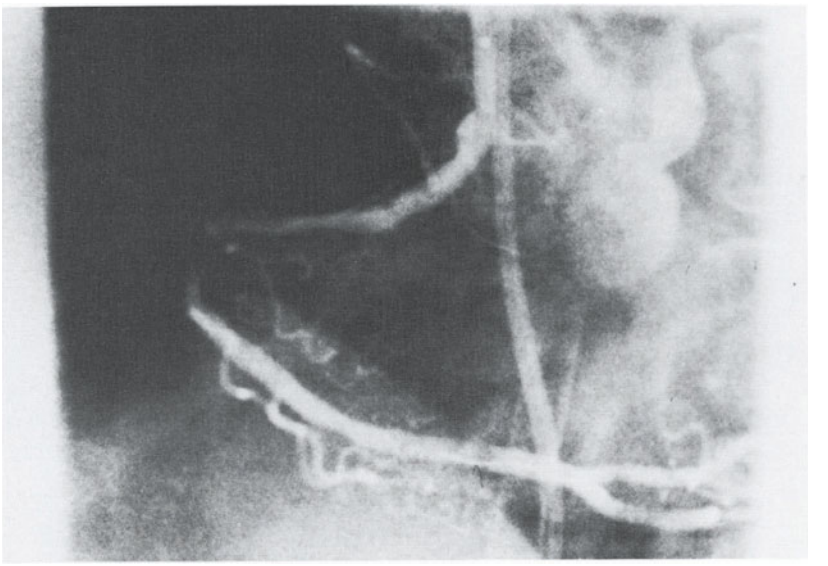

Figure 8-5. Coronary angiogram showing patent right coronary artery after PTCA.

in her sensorium. Coronary angiography revealed a totally occluded right coronary artery (RCA) (Figure 8-3) and critical narrowing of the proximal left anterior descending (LAD) and mid left circumflex (LCX) coronary arteries (Figure 8-4). Left ventriculography revealed a severely hypokinetic inferior wall and a moderately hypokinetic anterolateral wall, with a left ventricular ejection fraction of 29%. PTCA of the RCA was performed first with an excellent result (Figure 8-5). Repeat angiography 20 minutes later showed continued patency. Next, both the LAD and LCX were dilated with excellent angiographic results (Figure 8-6). After the procedure, the patient was gradually weaned off cardiopulmonary bypass in the catheterization laboratory with minimal inotropic support and infusion of 500 cc of fluid. Her ECG was improved after the procedure and she had an uneventful hospital course, with discharge 7 days postprocedure. A subsequent radionuclide ventriculogram revealed a left ventricular ejection fraction of 40% with moderate inferior hypokinesis and a normal anterolateral wall. Two months after discharge, a stress thallium study revealed a fixed inferior defect and no evidence of reversible ischemia.

COMMENTS

A variety of medications have been used in the treatment of cardiogenic shock. Vasopressors may be necessary to support blood pressure and coron-

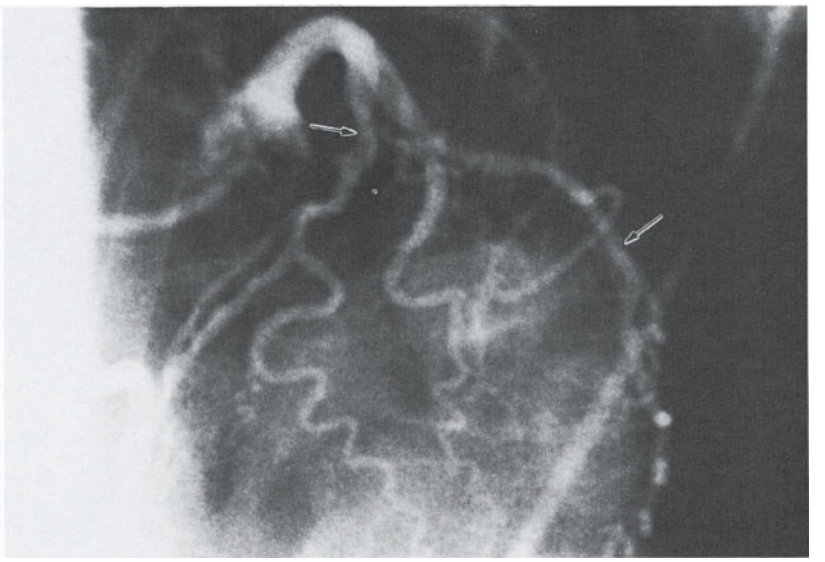

Figure 8-6. Coronary angiogram showing excellent post-PTCA result (arrows) in the left anterior descending and left circumflex.

ary perfusion, and inotropes may be used to increase contractile function [2]. The beta agonists dobutamine and dopamine are in common use, as is the phosphodiesterase inhibitor, amrinone. Vasodilators may increase the cardiac output by reducing the excessive vasoconstriction that often accompanies cardiogenic shock [19]. Because of the increase in cardiac output, the blood pressure may not be significantly reduced by these agents. Vasodilators can also reduce the left ventricular filling pressure [19], which results in a decrease in pulmonary congestion. Careful hemodynamic monitoring is necessary to avoid systemic hypotension. While pharmacologic therapy can provide temporary support to the failing heart and circulation, the prognosis does not appear to be altered unless more definitive therapy is undertaken [2].

The intraaortic balloon pump can reverse the shock state temporarily in most patients [20,21]. Scheidt [21], however, reported the results of a multicenter study in which 87 cardiogenic shock patients had a 90% mortality when treated with the intraaortic balloon pump without revascularization. As with pharmacologic therapy, mechanical circulatory support can temporarily stabilize patients in cardiogenic shock, but the outcome is not altered unless definitive therapy of the underlying lesion is undertaken.

Thrombolytic therapy has been shown to reduce mortality in acute myocardial infarction in some subsets [27–30]. However, in patients in cardiogenic shock, the outcome does not appear to be improved [30].

Revascularization by CABG has been suggested as a means of improving the prognosis of cardiogenic shock due to acute myocardial infarction. DeWood [26] studied 40 patients with cardiogenic shock. Twenty-one patients had conventional treatment, including institution of the intraaortic balloon pump. Nineteen underwent both early revascularization and placement of an intraaortic balloon pump. For patients who were operated on within 16 hours, there was a 75% survival rate. On the other hand, when CABG was performed more than 18 hours after the onset of symptoms, the survival rate was only 28.6%. There appeared to be a time threshold beyond which the usefulness of CABG substantially declined.

Other studies of CABG in the treatment of cardiogenic shock have been undertaken that have reported survival rates between 58% and 88% [27–29]. Such a survival rate is far higher than would be expected from medical management alone and provides compelling evidence of the benefit of revascularization.

A series of studies have been reported suggesting that coronary angioplasty can improve the prognosis of cardiogenic shock [34–36]. In these patients, survival ranged from 43% to 70%. Lee et al. [24] reported a large retrospective study of coronary angioplasty in the treatment of cardiogenic shock. Eighty-three patients were studied. The patients were separated into two groups. Group 1 (59 patients) was composed of patients who did not receive coronary angioplasty. They were treated conventionally with medications and with the intraaortic balloon pump, as deemed necessary. Group 2 (24 patients) received coronary angioplasty plus conventional therapy. The 30-day survival was 50% in group 2 and 17% in group 1. This study suggests that coronary angioplasty can improve survival in patients whose myocardial infarction is complicated by cardiogenic shock.

Of interest is the far higher mortality rate in patients with multivessel disease in Lee's series, despite successful angioplasty. This result led the authors to suggest that angioplasty in these patients be reserved for those with single-vessel disease. The data that we reported suggest that the survival is excellent when all lesions are dilated. The disparity between the two reports may be related to the hemodynamic stability provided by the use of cardiopulmonary bypass, as well as the performance of complete revascularization. Furthermore, there is experimental evidence [37] that reperfusion in an unloaded state may reduce reperfusion injury.

In patients with cardiogenic shock, mechanical circulatory support is often necessary to stabilize the patient sufficiently to perform PTCA. In some patients, the intraaortic balloon pump may be useful. In patients without an effective rhythm (such as those with ventricular fibrillation), or in those with sufficiently severe left ventricular dysfunction, the intraaortic balloon is ineffective (Figure 8-7). Cardiopulmonary bypass, on the other hand, can maintain adequate perfusion in the absence of effective cardiac function [23]. Other support devices may prove useful in the future. The Hemopump has been used to support patients in cardiogenic shock [37]. This device is a catheter with a

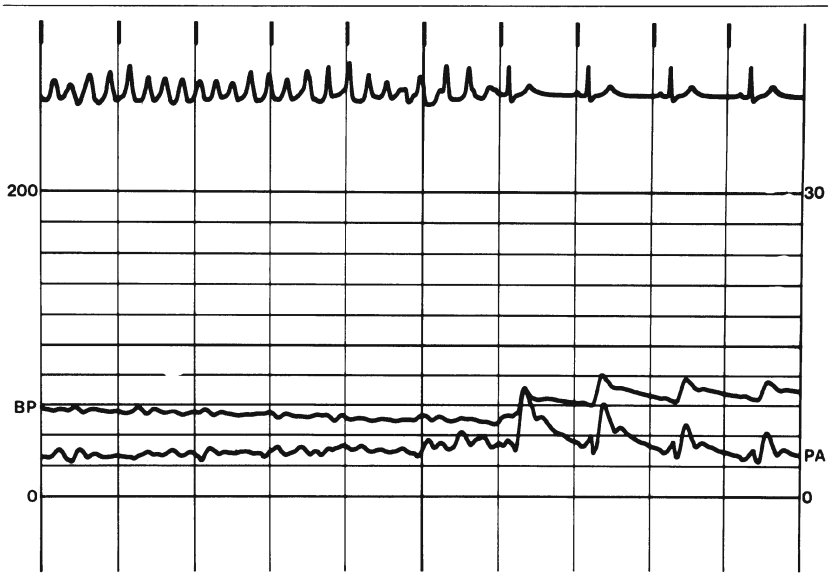

Figure 8-7. Cardiogenic shock patient on cardopulmonary bypass. The patient is awake with a well-maintained blood pressure (mean 58 mmHg), despite ventricular fibrillation following right coronary artery contrast injection. Note spontaneous reversion to normal sinus rhythm after approximately 90 seconds. BP = blood pressure; PA = pulmonary artery pressure.

pumping device mounted on the end. It is placed across the aortic valve and serves as a left ventricular assist device. It has the advantage of being able to provide support for a number of days. The present system has a 22 Fr distal end and must be placed by surgical cutdown. Further, the absence of guidewire guidance makes the device more difficult to place, particularly if the peripheral vasculature is diseased. If a smaller device could be placed percutaneously and was guidewire guided, the system might prove both practical and useful. The role of the Hemopump in cardiogenic shock is discussed by Wampler in Chapter 14. Other approaches to mechanical circulatory support may also be developed.

The authors believe that the data available suggest a paradigm for the treatment of cardiogenic shock. Patients who present with hypotension and signs of hypoperfusion following an acute myocardial infarction should have a pulmonary artery catheter placed. If the pulmonary capillary wedge pressure (PCW) is low, volume infusion should be used to increase blood pressure and to restore adequate perfusion. If the PCW is raised to 18–20 mmHg and the patient remains inadequately perfused, or if the initial PCW determination is >18–20 mmHg and the patient is hypotensive and poorly perfused, an intraaortic balloon pump may be added if the rhythm is appropriate. PCPS

should be instituted if the rhythm is unstable or the patient has very severely compromised pump function. After stabilization, coronary arteriography should be performed, followed by coronary angioplasty or coronary bypass grafting, if feasible. In cardiogenic shock patients with multivessel disease in whom multivessel PTCA is contemplated, PCPS should be instituted prior to any dilatation in order to maximize safety.

FUTURE DIRECTIONS

Substantial progress has been made in the treatment of acute myocardial infarction, but approaches that further limit infarct size are under study. Among the problems being addressed is reperfusion injury. One method of reducing reperfusion injury that appears promising is the infusion of a cardioplegic solution [39], which is accomplished by infusion of warm cardioplegic reperfusate, which includes substrates that buffer acidosis and limit the calcium load. Since this may lead to cardiac arrest, the prophylactic use of PCPS and left ventricular venting may be indicated.

CONCLUSIONS

Cardiopulmonary bypass support, instituted percutaneously in the catheterization laboratory, can stabilize patients in cardiogenic shock, allowing definitive diagnosis and treatment. Mortality appears to be improved in these patients when they are revascularized early in the course of shock.

REFERENCES

1. Weil MH, von Plotz M, Reckow EC. Acute circulatory failure (shock). In Braunwald E, ed, *Heart Disease: A Textbook of Cardiovascular Medicine*. W.B. Saunders, Philadelphia, 1988, pp. 561–590.
2. Laks H, Rosenkranz E, Buckberg GD. Surgical treatment of cardiogenic shock after acute myocardial infarction. *Circulation* 1986; 74(Suppl. III):III-11–III-16.
3. Resnekov L. Cardiogenic shock. *Chest* 1983; 83:893.
4. Aguess CM, Binder MJ. Cardiogenic shock. *Am Heart J* 1957; 54:458–477.
5. Sceidt S, Ascheim R, Kelly T. Shock after acute myocardial infarction: A clinical and hemodynamic profile. *Am J Cardiol* 1970; 26:556.
6. Kuhn LA. The treatment of cardiogenic shock. *Am Heart J* 1967; 74:578–587.
7. Binder MJ, Ryan JA, Marcus S, Mugler T, Strange D, Agress CM. Evaluation of therapy in shock following acute myocardial infarction. *Am J Med* 1955; 18:622.
8. Killip T, Kimball JT. Treatment of myocardial infarction in a coronary care unit: A two-year experience with 250 patients. *Am J Cardiol* 1967; 20:457.
9. Russell RD, Hunt D, Rackley CE. Left ventricular hemodynamics in anterior and inferior myocardial infarction. *Am J Cardiol* 1973; 32:8–16.
10. Gunnar RM, Loch HS, Rahimtoola SH. Hemodynamic studies in shock with myocardial infarction. In Gunnar RM, Loch HS, Rahimtoola SH, eds, *Shock in Myocardial Infarction*. Grune and Stratton, New York, 1974, pp. 113–130.
11. Prakesh R, Forrester J, Parmby WW. Prognostic implications of left ventricular stroke work index in acute myocardial infarction. *Clin Res* 1972; 20:395.
12. Ratshine RA, Rothby CE, Russell RO. Hemodynamic evaluation of left ventricular function in shock complicating myocardial infarction. *Circulation* 1972; 45:127–139.
13. Harnarayan C, Bennett MA, Pentecost BL, Brewer DB. Quantitative study of infarcted myocardium in cardiogenic shock. *Br Heart J* 1970; 32:728–732.
14. Wachers FJ, Lie KI, Becker AE, Durrer D, Wellers HJ. Coronary artery disease in patients

dying from cardiogenic shock or congestive heart failure in the setting of acute myocardial infarction. *Br Heart J* 1976; 38:906–910.
15. Morris DC, Walter PF, Hurst JW. The recognition and treatment of myocardial infarction and its complications. In Hurst JW, Rackley CE, Sonnenblick EH, Wenger NK, eds, *The Heart*. McGraw Hill, New York, 1990, pp. 1054–1078.
16. Gutovitz AL, Sobel BE, Roberts R. Progressive nature of myocardial injury in selected patients with cardiogenic shock. *Am J Cardiol* 1978; 41:469–475.
17. Alonso DR, Scheidt S, Post M, Killip T. Pathophysiology of cardiogenic shock: Quantification of myocardial necrosis, clinical, pathologic and electrocardiographic correlations. *Circulation* 1973; 48:588–596.
18. Scheidt S, Wilner G, Mueller H, Summers D, Lesch M, Walff G, Kahkauser J, Rubenfine M, Noon G, Oldhorn N, Killip T, Kantrowitz AR. Intra-aortic balloon counterpulsation in cardiogenic shock: Report of a cooperative trial. *N Engl J Med* 1973; 288:979–984.
19. Laude AJ, Edwards L, Bloch JH, et al. Clinical experience with emergency use of prolonged cardiopulmonary bypass with a membrane pump oxygenator. *Ann Thorac Surg* 1970; 10: 409–423.
20. Dunkman WB, Leinbach RC, Buckley MJ, Mundth ED, Kantrowitz AR, Austen WG, Sanders CA: Clinical and hemodynamic results of intra-aortic balloon pumping and surgery for cardiogenic shock. *Circulation* 1972; 46:465–477.
21. Shawl FA, Domanski MJ, Wish MH, et al. Emergency cardiopulmonary bypass support in patients with cardiac arrest in the catheterization laboratory. *Cathet Cardiovasc* 1990; 19: 8–12.
22. Phillips SJ, Ballentine B, Slonine D, et al. Percutaneous institution of cardiopulmonary bypass. *Ann Thorac Surg* 1983; 36:223–225.
23. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Emergency percutaneous cardiopulmonary bypass support in cardiogenic shock from acute myocardial infarction. *Am J Cardiol* 1989; 64:967–970.
24. Lee L, Bates ER, Pitt B, Walton JA, Laufer N, O'Neil WW. Percutaneous transluminal coronary angioplasty improves survival in acute myocardial infarction complicated by cardiogenic shock. *Circulation* 1988; 78:1345–1351.
25. Pasternak RC, Braunwald E, Sobel BE. Acute myocardial infarction. In Braunwald E, ed, *Heart Disease: A Textbook of Cardiovascular Medicine*. W.B. Saunders, Philadelphia, 1988, pp. 1222–1313.
26. Dewood MA, Natske RN, Hensley GR, Shields JP, O'Grady WP, Spores J, Goldman M, Ganji JH. Intra-aortic balloon counterpulsation with and without reperfusion for myocardial infarction shock. *Circulation* 1980; 61:1105–1112.
27. Gruppo Italiano per lo Studio della Strepchinasi nell'Infarcto Miocardico. Effectiveness of intravenous thrombolytic therapy in acute myocardial infarction. *Lancet* 1986; 1:397–401.
28. Wilcox RG, Olson CG, Silene AM, von der Lippe G, Jensen G, Hampton Jr. for the Asset Study Group. Trial of tissue plasminogen activator for mortality reduction in acute myocardial infarction — Anglo-Scandanavian Study of Early Thrombolysis (ASSET). *Lancet* 1988; 2:525–530.
29. Van de Werf F, Arnold AER. Investigation of the European Cooperative Study Group for recombinant tissue type plasminogen activator (rt-Pa). Intravenous tissue plasminogen activator and size of infarct, left ventricular function, and survival in acute myocardial infarction. *Br Med J* 1988; 297:1374–1379.
30. Mathey D, Kuck KH, Tilsner V, Krehber HJ, Bleifield W. Nonsurgical coronary artery reconclization in acute transmural myocardial infarction. *Circulation* 1981; 63:489–497.
31. Laks H, Rosenbranz E, Buckberg GD. Surgical treatment of cardiogenic shock after myocardial infarction. *Circulation* 1986; 74(Suppl. III): III-11–III-15.
32. Phillips SJ, Zeff RH, Skinner JR, Toon RS, Grignon A, Kongtahworn C. Reperfusion protocol and results in 738 patients with evolving myocardial infarction. *Ann Thorac Surg* 1986; 41:119–125.
33. Guyton RA, Arcidi JM Jr., Langford DA, Morris DC, Liberman HA, Hatcher CR Jr. Emergency coronary bypass for cardiogenic shock. *Circulation* 1987; 76(Suppl. V):V-22.
34. Shani J, Rivera M, Greengart A, Hollander G, Kaplan P, Lichstein E. Percutaneous transluminal coronary angioplasty in cardiogenic shock. *J Am Coll Cardiol* 1986; 7:149A.
35. Brown TM Jr., Iannone LA, Gordon DF, Wickemeyer WJ, Wheeler WS, Rough RR. Per-

cutaneous myocardial perfusion (PMR) reduces mortality in acute myocardial infarction (MI) complicated by cardiogenic shock. *Circulation* 1985; 72:III-309.
36. O'Neil W, Erber R, Laufer N, et al. Coronary angioplasty therapy of cardiogenic shock complicating acute myocardial infarction. *Circulation* 1985; 72:III-309.
37. Laschinger JC, Grossi EA, Gunningham JN, et al. Adjunctive left ventricular unloading during myocardial reperfusion plays a major role in minimizing myocardial infarct size. *J Thorac Cardiovasc Surg* 1985; 90:80–85.
38. Smalling RW, Cassidy DB, Merhige M, et al. Improved hemodynamic and left ventricular unloading during acute ischemia using the hemopump left ventricular assist device compared to intra-aortic balloon counter pulsation. *J Am Coll Cardiol* 1989; 13:160A.
39. Allen BS, Okamoto F, Buckberg GD, et al. Studies of controlled reperfusion after ischemia. XV. Immediate functional recovery after 6 hours of regional ischemia by careful control of conditions of reperfusion and compostion of reperfusate. *J Thorac Cardiovasc Surg* 1986; 92(Suppl. 3):621.

9. EMERGENCY PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT IN PATIENTS WITH CARDIAC ARREST

FAYAZ A. SHAWL

INTRODUCTION

Basic investigation into circulatory support carried out in the 1960s and early 1970s [1–3] resulted in the development of the intraaortic balloon pump [4–6] and cardiopulmonary bypass [7,8].

In 1967, Drs. Proctor and Kowalik reported 16 cases of intractable ventricular fibrillation induced in dogs with subsequent successful circulatory support using cardiopulmonary bypass with peripheral cannulation [9]. This study suggested that cardiopulmonary bypass facilitates successful defibrillation and reduces the region of ischemia distal to a ligated coronary artery.

Similar results were obtained by Evans [10], who reported spontaneous reversion to sinus rhythm from prolonged ventricular fibrillation in dogs who were placed on bypass.

Lunde et al. [1] reported 18 patients with cardiogenic shock, cardiac arrest, or respiratory failure who were placed on cardiopulmonary bypass support in the emergency room, intensive care unit, or operating room. Sixteen showed improvement and three patients were long-term survivors. In 1971, Bricker et al. [11] reported the use of cardiopulmonary bypass support in 32 patients, of whom 22 recovered and survived long term.

In 1972, Baird [12] reported the use of cardiopulmonary support in 25 patients in cardiac arrest due to myocardial infarction. All patients improved and 28% survived with this technique. Mattox et al. [13] reported the application of portable cardiopulmonary bypass support in patients with cardiac

arrest due to a variety of conditions, including trauma, gunshot wounds to the chest, and massive drug overdose. Of 43 patients, there were 17 survivors. In 1982, Phillips and coworkers reported the use of percutaneous initiation of cardiopulmonary bypass support in five patients with refractory cardiac arrest. All five patients were resuscitated with this technique [14].

These studies demonstrated the efficacy of this form of circulatory support in achieving initial hemodynamic stabilization. The long-term outcome, however, was disappointing in these studies. This may have been due to either the delay in establishing circulatory support or to the absence of definitive therapy for the underlying disease. However, after studies in animals and humans, a number of therapeutic uses for emergency cardiopulmonary bypass support have been identified (Table 9-1).

CLINICAL EXPERIENCE IN PATIENTS WITH CARDIAC ARREST

Studies of the application of this form of extracorporeal circulatory support in the resuscitation of patients who sustain cardiac arrest in the catheterization laboratory due to abrupt closure, cardiogenic shock, or diagnostic angiography have been undertaken.

Kanter et al. [7] were the first to report the use of cardiopulmonary bypass support instituted in the catheterization laboratory. They used femoral cutdown to insert cannulae in patients with cardiac arrest following failed angioplasty. All patients achieved hemodynamic stability on cardiopulmonary bypass, and 2 of the 3 patients in whom emergency cardiopulmonary bypass surgery was performed survived. Subsequently, the author introduced the technique of percutaneous cardiopulmonary bypass support (PCPS) using 18 Fr or 20 Fr cannulae in patients undergoing emergent, as well as elective, high risk interventions [8,15–20]. In the author's experience [18], as well as that of others [21], there is improved survival when instituted percutaneously. There is a delay in instituting bypass cannulation by surgical cutdown, particularly in the cardiac catheterization laboratory.

One of the most important indications for percutaneous cardiopulmonary

Table 9-1. Suggested use of emergent cardiopulmonary bypass support

Cardiac arrest (early)
Myocardial infarction
Pulmonary embolism
Cardiogenic shock
Severe congestive cardiac failure
Drug overdose
Hypothermia
Hemorrhagic shock
Drowning
Alveolar hypoproteinosis
Ruptured septum/left ventricle

bypass support is catheterization laboratory cardiac arrest. This topic is the subject of the remainder of this chapter.

ABRUPT CLOSURE DURING CORONARY ANGIOPLASTY: ROLE OF CARDIOPULMONARY BYPASS SUPPORT

Although procedural complications during elective coronary angioplasty are relatively infrequent, the absolute numbers are substantial, given the large and increasing number of angioplasties now performed in the United States and elsewhere.

Complications of coronary angioplasty include myocardial infarction and death, which usually result from ischemia initiated by acute closure of the dilated artery. This acute closure can occur either inside the catheterization laboratory during the course of angioplasty or outside the catheterization laboratory following the procedure. The incidence of acute closure in the catheterization laboratory ranges from 2 to 5%, and many [34–76%] of these patients require emergency coronary bypass graft surgery. Such surgery is associated with a 35–56% incidence of acute myocardial infarction and a mortality rate of approximately 5% [22–26]. Patients who sustain cardiac arrest in the catheterization laboratory due to abrupt closure, which is not immediately reversible by repeat dilatation, are at highest risk. The rapid institution of cardiopulmonary bypass support in the catheterization laboratory in such patients can stabilize the patient, allowing repeat angiography and subsequent treatment of abrupt closure by using repeat dilatation or emergency bypass surgery.

OTHER APPLICATIONS IN THE CATHETERIZATION LABORATORY

Severe hemodynamic compromise or cardiac arrest due to an interventional or diagnostic procedure can be dealt with immediately using cardiopulmonary bypass support. We and others have used this tool to resuscitate patients who suffer cardiac arrest in the catheterization laboratory [18,21,27]. This powerful technique should be available in every catheterization laboratory, particularly those that treat high risk patients. The current systems for bypass support are very effective, but the ideal circulatory support that would also maintain coronary perfusion and be usable for prolonged periods of time does not yet exist (Table 9-2).

Table 9-2. Ideal circulatory support

Maintain systemic perfusion
Maintain coronary perfusion
Easy access
Used for extended periods

CASE EXAMPLES

Abrupt closure with cardiac arrest

Case 1

A 72-year-old man with previous anterior myocardial infarction presented with recurrent angina. Cardiac catheterization revealed akinetic anterolateral-apical segments with an ejection fraction of 35%, a totally occluded left anterior descending artery, and critical stenosis in the proximal, dominant left circumflex (Figure 9-1A). Angioplasty of the left circumflex was undertaken with a 3-mm balloon. Angiography following dilatation revealed dissection at the angioplasty site with compromised distal flow (Figure 9-1B). The patient developed chest pain, ST-segment depression, and hypotension. An intraaortic balloon pump was rapidly inserted from the contralateral groin and inotropic support was begun. The patient continued to deteriorate, with recurrent episodes of ventricular fibrillation. Following initiation of cardiopulmonary resuscitation, the intraaortic balloon pump was removed and cardiopulmonary bypass was instituted (Figure 9-2A). A mean blood pressure of 75 mmHg was achieved at a flow rate of 5 l/min. The patient regained consciousness and became responsive while still in ventricular fibrillation. He was converted to normal sinus rhythm after the administration of intravenous diazepam. An unsuccessful attempt was made to recross the stenosis. He was then transferred to the operating room for emergency bypass surgery. He was discharged 10 days later and remains asymptomatic 2 years later.

A 67-year-old woman with previous anterior myocardial infarction underwent cardiac catheterization because of Class II angina. Angiography revealed severely hypokinetic anterolateral and posterolateral segments, with a left ventricular ejection fraction of 33%, a total proximal occlusion of the left anterior descending, total occlusion of the left circumflex after the takeoff of the first marginal branch (which was 90% stenosed at its origin), and a 90%, discrete stenosis of a large right coronary artery. Initially successful angioplasty of the right coronary artery and first obtuse marginal branch was performed. Fifteen minutes later, just prior to transfer from the catheterization laboratory, the patient developed chest pain and hypotension with ST elevation and deteriorated rapidly to cardiac arrest. Cardiopulmonary bypass was instituted 10 minutes after cardiac arrest using the angioplasty access sites (arterial and venous) with the patient asystolic (Figure 9-3). Arterial access was obtained using the contralateral groin. With a bypass flow of 5 l/min (mean blood pressure 95 mmHg), the patient who was initially asystolic,

---

Figure 9-1. *A*: Left coronary angiogram prior to coronary angioplasty demonstrating critical stenosis proximal to the first obtuse marginal branch, patent ramus intermedians, and a totally occluded left anterior descending. *B*: Left coronary angiogram after coronary angioplasty, revealing a large dissection (arrow) and poor distal runoff.

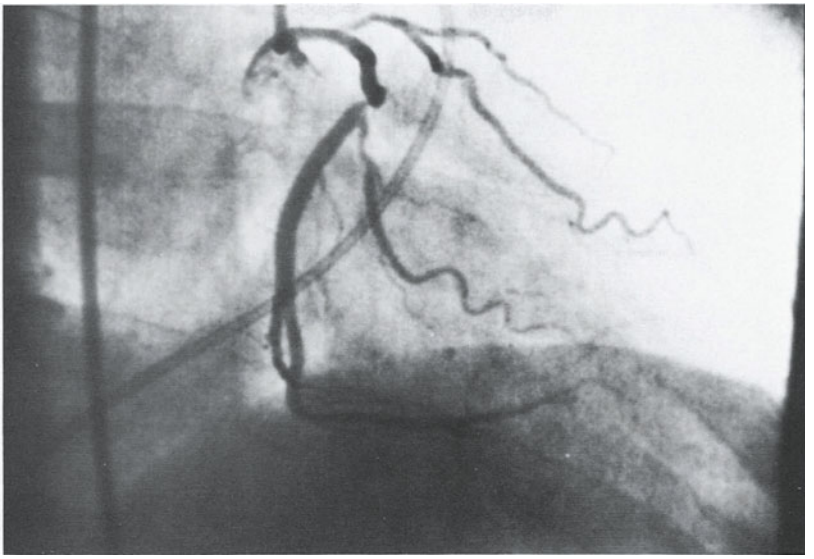

Figure 9-1A

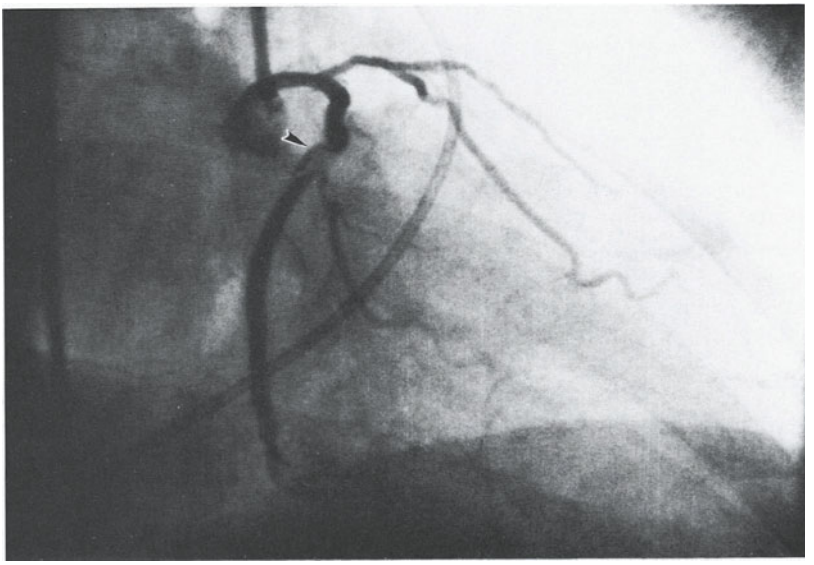

Figure 9-1B

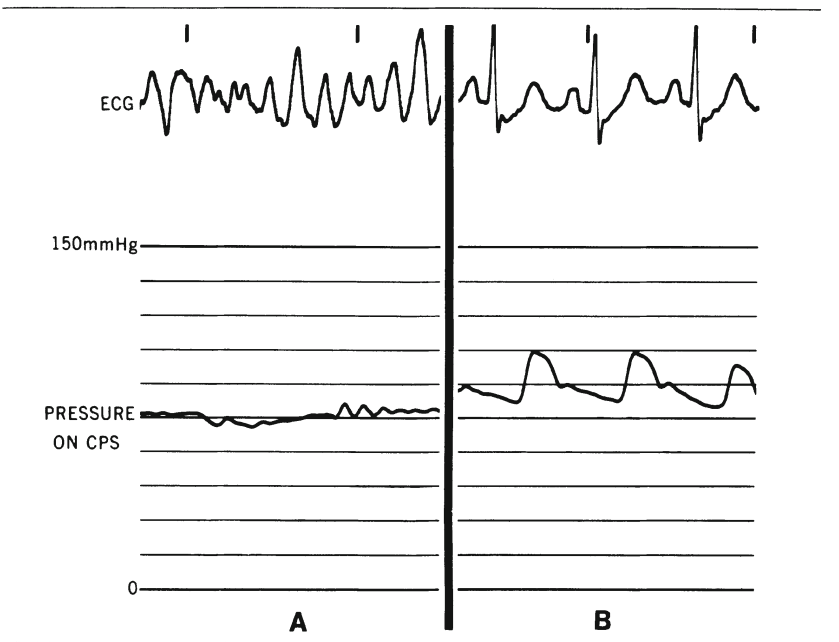

Figure 9-2. *A*: A mean blood pressure of 75 mmHg on cardiopulmonary support (CPS) at a flow rate of 5 l/min. Note that the ECG demonstrates ventricular fibrillation with the patient awake and responsive to verbal command. *B*: After defibrillation and prior to emergency coronary bypass graft surgery. From Shawl et al., Emergency cardiopulmonary bypass support with cardiac arrest in the catheterization laboratory. *Cathet Cardiovasc Diag* 1990; 19:8–12. With permission.

developed a junctional rhythm followed by ventricular fibrillation (Figure 9-4A). The patient became responsive 10 minutes after PCPS was started following successful defibrillation, and there was evidence of excellent ventricular ejection (Figure 9-4B). Repeat angiography revealed patency of the obtuse marginal, but a subtotal occlusion of the right coronary artery at the angioplasty site, as well as multiple filling defects secondary to thrombi (Figure 9-5). Repeat angioplasty was successfully performed using a 5-minute balloon inflation. The patient was easily weaned off bypass and required no subsequent mechanical circulatory support. The postangioplasty electrocardiogram was essentially unchanged. There was a modest increase in CPK-MB. This patient remains asymptomatic a year after discharge.

Case 3

A 53-year-old man was admitted for an elective coronary angioplasty of the proximal left anterior descending coronary artery because of recent angina and

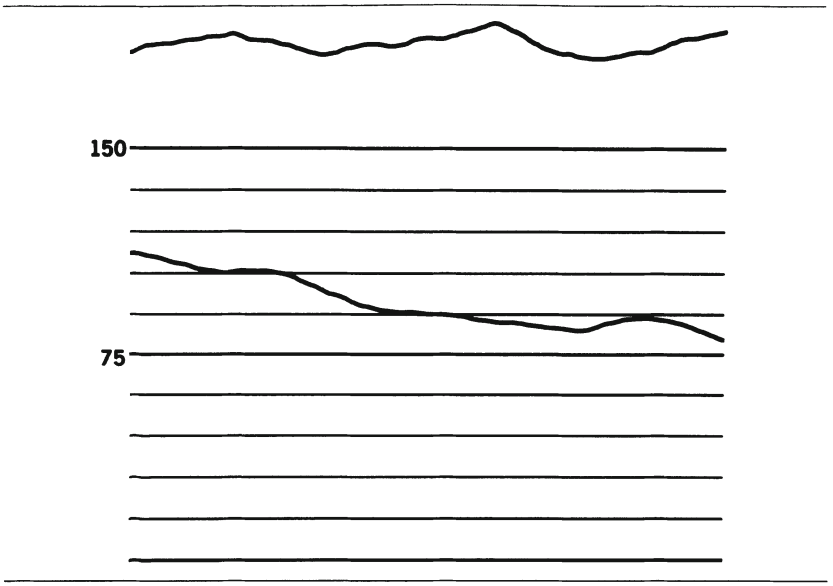

Figure 9-3. A mean blood pressure of 95 mmHg on cardiopulmonary bypass support at a flow rate of 5 l/min in a patient who sustained a cardiac arrest postangioplasty. Note that the ECG demonstrates asystole.

a markedly abnormal low-level stress thallium study. Initially, he had a successful angioplasty with a residual stenosis of 30% and a small, nonobstructing dissection with excellent distal runoff. Ten minutes later, the patient complained of chest pain and ST segment elevation was noted on the monitor. Repeat angiography revealed total occlusion of the left anterior descending. During an attempt to cross the lesion with a Stack perfusion catheter, the patient became hypotensive, followed shortly by cardiac arrest. While chest compressions were in progress, cardiopulmonary bypass was instituted (within 15 minutes of cardiac arrest) using the angioplasty access sites. Arterial and venous access for angiography, hemodynamic monitoring, and angioplasty were obtained using the contralateral groin. While the patient was still in ventricular fibrillation, a mean blood pressure of 75 mmHg was obtained, with a mean pulmonary artery pressure of 20 mmHg (Figure 9-6). The patient was defibrillated into normal sinus rhythm. Repeat angiography revealed a totally occluded left anterior descending coronary artery (Figure 9-7A). Using a 3.5-mm balloon and a 0.018-in., high-torque, floppy guidewire, the lesion was easily crossed and dilated (Figure 9-7B), using low-pressure and prolonged inflations (6 minutes). The patient was weaned smoothly from bypass and required no further mechanical or inotropic support. The bypass cannulae were left in place overnight for use in the event of abrupt closure. The patient

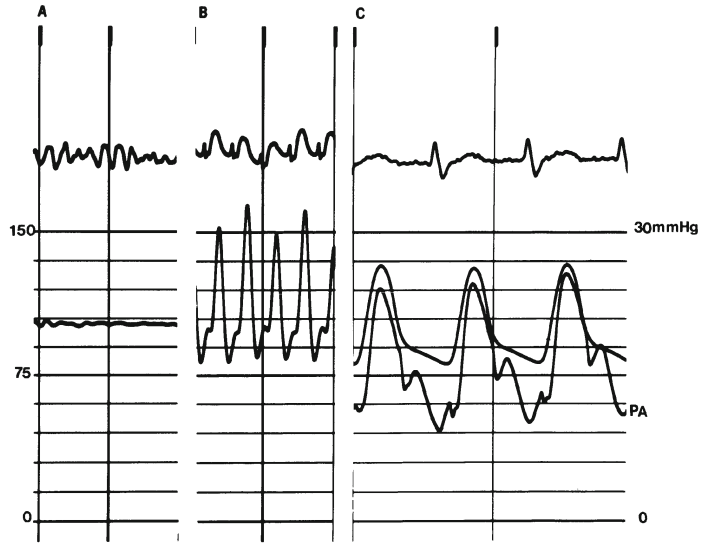

Figure 9-4. *A*: Mean blood pressure (BP) of 104 mmHg on bypass at a flow rate of 5 l/min (note that the rhythm is ventricular fibrillation; the patient was awake). *B*: After defibrillation the blood pressure was 150/84 mmHg (note ST-segment elevation). *C*: After successful repeat angioplasty of the right coronary artery with BP of 134/84 mmHg and pulmonary artery (PA) pressure of 26/10 mmHg following termination of bypass support. From Shawl, FA. Percutaneous cardiopulmonary bypass support in high risk interventions. *J Inv Cardiol* 1989; 1:287–293. With permission.

was anticoagulated with heparin, keeping the activated clotting time between 220 and 280 seconds. The EKG was normal but there was a small increase in CPK-MB and the patient was discharged 6 days later without further revascularization.

Cardiac arrest complicating diagnostic and other interventional procedures

Case 1

A 68-year-old woman undergoing diagnostic catheterization in an outpatient laboratory suffered a cardiac arrest following angiography of the left coronary artery. Despite application of advanced cardiac life support, resuscitation was unsuccessful. Forty-five minutes were necessary to move cardiopulmonary support equipment from the adjacent hospital. The patient was placed on cardiopulmonary bypass and a mean blood pressure of 70 mmHg was obtained using a flow of 5.5 l/minute (Figure 9-8) with resumption of an intrinsic rhythm. Because of the presence of critical left main stenosis and severe three-vessel coronary disease, she underwent emergency coronary bypass graft

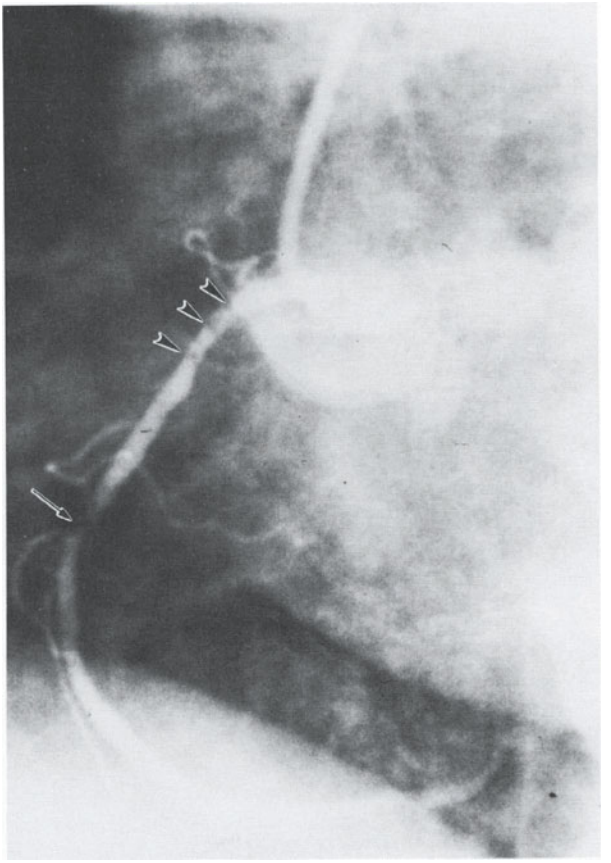

Figure 9-5. Right coronary angiogram following cardiopulmonary arrest with patient still on cardiopulmonary bypass showing a subtotal occlusion at the site of the previous angioplasty (narrow) and multiple filling defects secondary to coronary thrombi (arrowheads). Note the poor distal runoff.

surgery 100 minutes later. The patient died after surgery due to low cardiac output.

Case 2

A 71-year-old man was undergoing mitral valvuloplasty for severe mitral stenosis. The patient had an uneventful transseptal catheterization and the mitral valve was successfully crossed. While balloon dilatation of the mitral valve was in progress, the patient became hypotensive, followed by the develop-

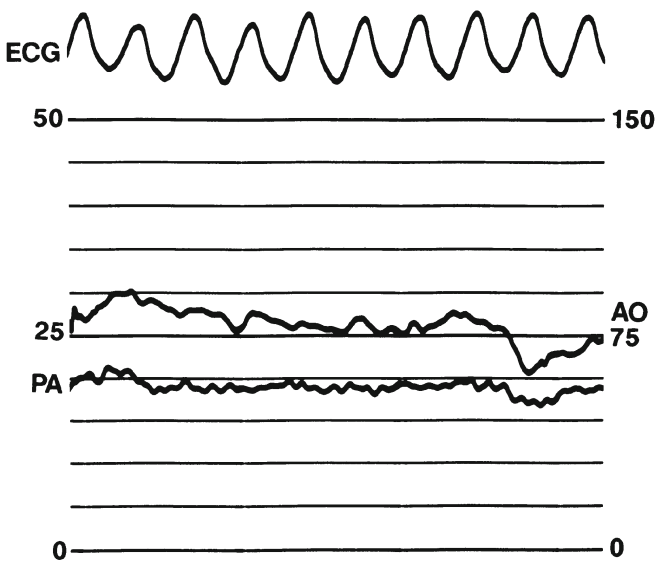

Figure 9-6. A mean blood pressure of 75 mmHg on cardiopulmonary bypass support at a flow rate of 4.0 l/min with ventricular fibrillation on ECG. Note pulmonary artery (PA) pressure of 20 mmHg.

ment of electromechanical dissociation. There was no response to attempted resuscitation. Within 10 minutes he was placed on cardiopulmonary bypass using the already present catheter access sites. Hemodynamic stability was immediately achieved and normal sinus rhythm resumed spontaneously. Echocardiography revealed a large pericardial effusion with evidence of tamponade. Left ventriculography demonstrated rupture of the left ventricular apex (Figure 9-9). The patient was subsequently transferred on cardiopulmonary bypass support for emergency surgery. The left ventricle was repaired and the mitral valve was replaced by a prothesis. At the time of surgery no mitral valve disruption was noted, but the valve appeared thickened and calcific. The patient was discharged and remains in Class I [19].

TECHNIQUE OF EMERGENT PERCUTANEOUS CARDIOPULMONARY BYPASS SUPPORT

A detailed description of the institution of percutaneous cardiopulmonary bypass support (PCPS) in the catheterization laboratory is provided by the author in Chapter 6. Basically, cardiopulmonary bypass support cannulae are inserted after replacing the already present arterial and venous catheters. However, the author has also used direct institution of the cardiopulmonary bypass support system in patients who have sustained cardiac arrest just prior

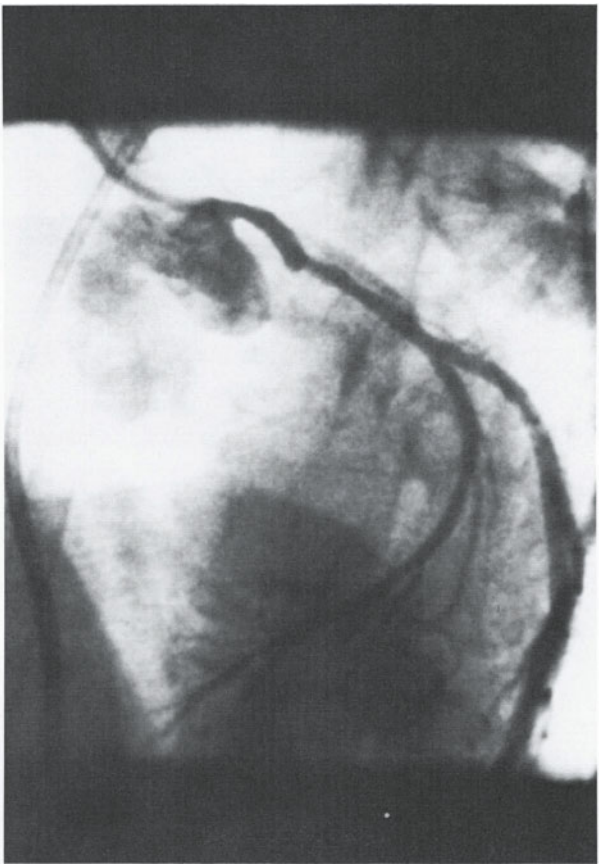

Figure 9-7A

Figure 9-7. *A*: Left coronary angiogram after achievement of hemodynamic stability on cardiopulmonary bypass. Note total occlusion of the left anterior descending coronary artery at the angioplasty site. *B*: Repeat coronary angiogram after successful angioplasty showing widely patent vessel with excellent runoff.

to intervention or immediately after cardiac arrest outside the catheterization laboratory. In these cases, one should first cannulate the right femoral artery while cardiopulmonary resuscitation, including chest compressions, is in progress. PCPS can be rapidly instituted if cardiac arrest occurs after femoral venous and arterial access has been obtained. In patients with an intraaortic balloon pump catheter in place, the balloon can be removed over a 0.035-in. guidewire and then CPS cannulae can be inserted using the previously described technique. While cannulation is in progress, a perfusionist primes the

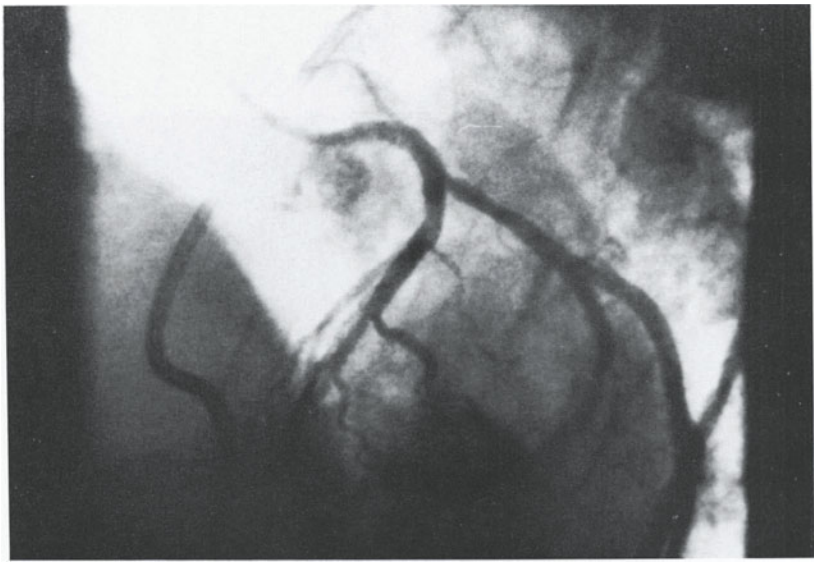

Figure 9-7B

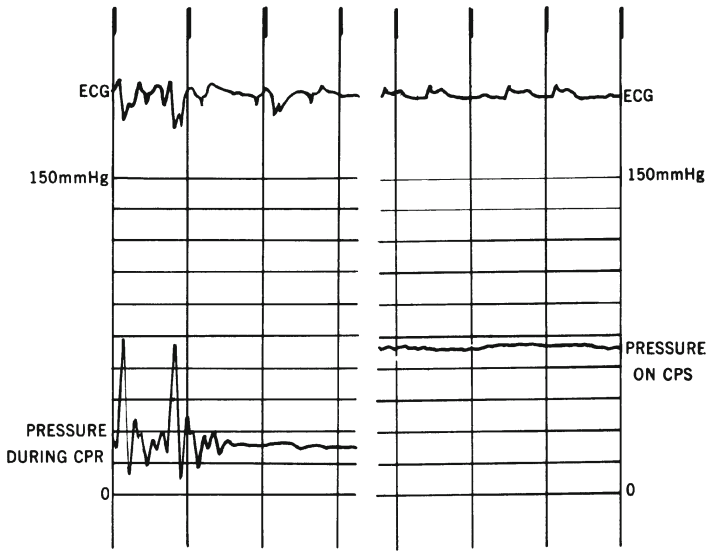

Figure 9-8. Pressure during cardiopulmonary resuscitation (CPR) with paced rhythm (left panel) and on cardiopulmonary bypass (CPS) (right panel). Note resumption of intrinsic rhythm with a blood pressure of 70 mmHg. From Shawl FA. Percutaneous cardiopulmonary bypass support in high risk coronary angioplasty. *Cardiol Clin* 1989; 87(4):865–875. With permission.

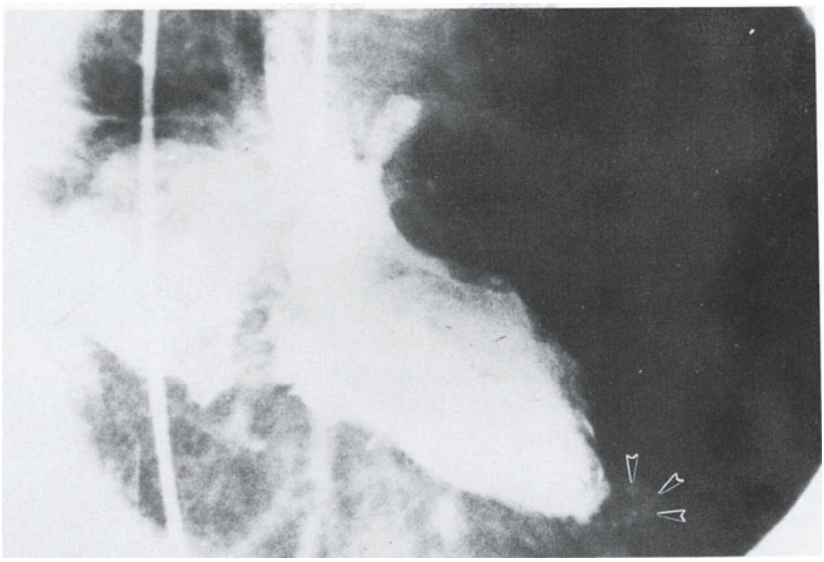

Figure 9-9A

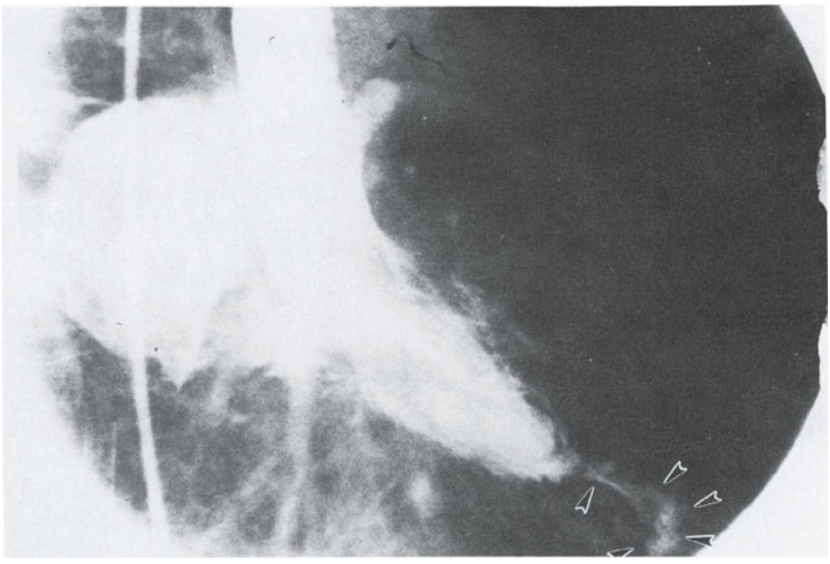

Figure 9-9B

Figure 9-9. *A*: Left ventriculogram in diastole. Note presence of contrast material in the pericardial space (arrowheads). *B*: Jet of contrast material entering the pericardial space during systole (arrowheads). From Shawl FA et al. Left ventricular rupture complicating percutaneous mitral commissurotomy: Salvage using percutaneous cardiopulmonary bypass support. *Cathet Cardiovasc Diag* 1990; 21:26–29. With permission.

perfusion circuit. Iliofemoral angiography is not performed in patients who present with cardiac arrest.

After the patient has been placed on the cardiopulmonary bypass support system, the contralateral femoral vessels are used for angiography and intervention. With experience, it takes less than 4 minutes to cannulate a patient for PCPS using the author's technique after venous and arterial access is obtained.

INITIATION OF CARDIOPULMONARY BYPASS SUPPORT

In patients in cardiac arrest, an estimate of necessary arterial blood flow can be calculated based upon the patient's body surface area or body weight. The optimal flow is 2.2–2.4 l/min/m or 50–60 ml/kg body weight. Activated clotting time is measured every 15 minutes and maintained at/or about 400 seconds after heparinization using 250–300 U/kg. Arterial blood gas, mixed venous oxygen saturation, and electrolytes are determined periodically in all patients. Patients who sustain cardiac arrest are intubated. They should not receive more than 21% oxygen while on bypass.

SUBSEQUENT THERAPY IN CARDIAC ARREST

Patients in cardiac arrest who are in ventricular fibrillation should be defibrillated. Patients who are initially asystolic generally return to normal sinus or junctional rhythm within a few minutes following the institution of cardiopulmonary bypass support. In such cases, pacemaker insertion has never been required in the author's experience. Patients who need emergency bypass graft surgery should be transported immediately to the operating room on PCPS, which is terminated after standard cardiopulmonary bypass support is used.

In patients with abrupt closure in the catheterization laboratory, leading to cardiac arrest, repeat angioplasty using prolonged balloon inflations should be used. Atherectomy, stenting or laser balloon angioplasty, may prove to be useful adjunctive therapy in these patients.

TERMINATION OF CARDIOPULMONARY BYPASS SUPPORT

In these patients cannulae are left in place until definitive therapy is undertaken. If the patient is sent for emergency coronary bypass or other surgical procedures, PCPS is terminated after conventional bypass (right atrium aorta) is instituted. In these patients, femoral bypass cannulae are removed by the surgeon after completion of the surgical procedure and the femoral artery and vein are sutured under the direct vision. In patients in whom a successful repeat angioplasty is performed and antegrade flow is established, cardiopulmonary bypass is terminated gradually (see Chapter 6 for termination procedure). Cannulae can be left in place for up to 24 hours. A cardiopulmonary bypass support system, along with the perfusion circuit primed, should be kept at patient's bedside in case of abrupt closure. These patients are heparinized and the partial thromboplastin time is regulated at 90 ± 10 seconds. The cannulae are then removed as described in Chapter 6.

Patients in whom neither angioplasty nor coronary bypass or other surgical procedures are possible are transported to the coronary care unit on PCPS. In this group, every effort is made to get the patient off bypass in less than 6–7 hours. Other circulatory support, for example, an intraaortic balloon pump, may be necessary to help in weaning the patient using the contralateral groin.

EXPERIENCE AND RESULTS

The author and his associates reported seven patients [18], five males and two females aged 56–81 years, who sustained cardiopulmonary arrest in the catheterization laboratory and did not respond rapidly to advanced cardiac life support (ACLS). Cardiac arrest occurred following abrupt closure post-coronary angioplasty in three patients, during cardiogenic shock with diagnostic angiography in three patients, and during elective diagnostic angiography in one patient. We recently instituted the cardiopulmonary bypass support system in two patients who sustained cardiac arrest due to repture of left ventricle during mitral valvuloplasty [19]. We have also reported gratifying results in other emergencies in the catheterization laboratory, including abrupt closure post-stent implantation, as well as during aortic valvuloplasty.

In the seven patients reported [19], PCPS was instituted successfully in all patients 10–45 minutes following cardiac arrest (mean = 21). The support was instituted more than 25 minutes following cardiac arrest in only one patient. All patients received chest compression prior to PCPS, and all patients were in ventricular fibrillation or asystole.

Flow rates on bypass ranged from 4.0–5.2 l/min. Mean blood pressure ranged from 70 to 110 mmHg, average 81 mmHg, while the rhythm was either ventricular fibrillation or asystole. In three patients, pulmonary capillary wedge pressure was monitored on bypass and was found to be <8 mmHg with evidence of left ventricular ejection on the aortic pressure tracing. However, patients with prolonged cardiac arrest and the institution of cardiopulmonary bypass support, generally demonstrate higher filling pressures, particularly if there is no ejection or there is ongoing ischemia. Six of the seven patients regained consciousness within 20 minutes of the start of PCPS, with three patients awake and responding to verbal commands while still in ventricular fibrillation. Only one patient in this report did not regain consciousness prior to bypass surgery after PCPS was instituted. This was the only patient in whom bypass was initiated 45 minutes after cardiac arrest. Total bypass time in this group was 1.5–8.5 hours, with a mean of 2.7 hours. Mixed venous oxygen saturation levels were determined in all patients on bypass and were >69% in all patients without any evidence of metabolic acidosis. Of the three patients with abrupt closure, two underwent emergency bypass surgery and one had successful repeat dilatation. All three of these patients survived. One of the three patients in cardiogenic shock underwent successful coronary angioplasty and survived. The other two patients had vessels unsuitable for either coronary angioplasty or coronary bypass surgery, and expired 0.5 and 7.5 hours after PCPS was terminated. The patient who

underwent emergency bypass surgery following cardiac arrest during diagnostic angiography, in whom PCPS was instituted 45 mintues later, could not be weaned from conventional cardiopulmonary bypass and expired.

Since this report [18], percutaneous cardiopulmonary bypass support in the catheterization laboratory has also been used in cardiac arrest due to both right and left ventricular perforation during mitral valvuloplasty, and abrupt closure in three patients, either due to angioplasty or stenting. All four patients survived, three requiring surgical intervention and one requiring repeat angioplasty in the catheterization laboratory. The largest group of patients receiving cardiopulmonary bypass support during cardiac arrest has been reported by Reichmond et al. [27]. In this study 38 patients had cardiopulmonary bypass support due to cardiac arrest that was refractory to ACLS. Percutaneous or cutdown cannulation was used, using the right femoral vein and femoral artery (n = 18), right internal jugular vein-femoral artery (n = 2), right atrium-ascending aorta (n = 2), or a combination approach (n = 4). Two patients could not be cannulated in this series. Patient's diagnoses were pulmonary emboli (n = 3), failed coronary angioplasty (n = 7), myocardial infarction with cardiogenic shock (n = 5), trauma (n = 7), aortic stenosis (n = 2), postcardiotomy deterioration (n = 10), deterioration after cardiac transplant (n = 2), cardiomyopathy shock (n = 1), and rupture of the ascending aorta (n = 1). Ninety-five percent of the patients were successfully resuscitated to a stable rhythm. Eight diagnostic procedures (coronary angiography in four, pulmonary angiography in three, aortagraphy in one) were performed while patients were on cardiopulmonary bypass support. Sixty-six percent (24 of 36 patients) successfully underwent conversion to standard cardiopulmonary bypass with subsequent operative procedure or placement of ventricular assist devices or total artificial heart. Fifty percent (18 of 36), of patients were successfully weaned from cardiopulmonary bypass support and 17% (6 of 36) of patients are long-term survivors. Thus, cardiopulmonary support salvaged six patients in their series of 38 patients who were not resuscitable by conventional means. Survival was directly related to early implementation and reversibility of the condition that lead to the patient's cardiac arrest.

LIMITED SUCCESS WITH EMERGENCY USE OF CARDIOPULMONARY BYPASS SUPPORT

It is now becoming increasingly clear that patients who have been sustained on cardiopulmonary bypass who have survived are those in whom PCPS was instituted during the first 10–20 minutes of arrest. This can best be achieved in the catheterization laboratory. The success in the institution of cardiopulmonary bypass support outside the catheterization laboratory is limited due to the delay in insertion, delayed decision making, and no fluroscopic guidance. However, technical advancement in cannulae and proper training in the utilization of the portable cardiopulmonary bypass system may result in an improvement in outcome in these patients in the future.

DISCUSSION

Cardiac arrest with sudden cardiac death accounts for approximately 300,000 deaths in the United States annually [28]. The technique of closed-chest massage for cardiopulmonary resuscitation was popularized by Dr. William Kouwenhoven and associates at John Hopkins in 1960 [29]. Since then, various methods of circulatory assistance have been applied to cardiopulmonary resuscitation technique in an effort to improve survival [30,31]. Results of cardiopulmonary resuscitation are a function of the mechanism and location of arrest, as well as the underlying pathology. In 1983, Bedell and coworkers [32] reported that only 14% of patients who survived in-hospital cardiac arrest were successfully discharged. Even with improved cardiopulmonary resuscitation technique, not much has changed since its introduction. Closed cardiac massage can provide only 10% of normal cerebral blood flow and only 14% [33] of patients are discharged alive. Use of open-chest cardiac massage may well provide better blood flow to these critical areas, but is not practical.

The concept of extracorporeal cardiopulmonary bypass support was introduced by LeGallois in 1813, but did not become a clinical reality until 1953 by Gibbon [34]. The initial indication for cardiopulmonary bypass support was to provide adequate systemic circulation in patients with a massive pulmonary embolus. The simple pump oxygenator rapidly evolved into a massive device requiring four roller pumps. This, coupled with unacceptable embolic rates and disruption of formed blood elements, slowed the clinical progress. Then, the concept of veno-venous and veno-arterial bypass was introduced. Goldman and colleagues [35] showed superior performance of veno-arterial pumping in ventricular fibrillation. Due to direct access to the venous reserve, increased preload could be delivered to the system and high flows could be obtained. Use of the membrane oxygenator lessens the problem of disruption of the formed blood elements with prolonged perfusion. Techniques of percutaneous femoral cannulation [37,38], along with an improved understanding of extracorporeal perfusion, led to the development of the portable cardiopulmonary bypass system that is now used. The author, and others, have used PCPS in patients in whom ACLS was ineffective and in whom fatal arrhythmia was believed to be irreversible. We have also used it in cardiac arrest patients in whom the diagnosis was unclear, and in such patients PCPS provided time to perform diagnostic studies. When angiography is performed, PCPS flow rate must be reduced and the heart allowed to eject. Also, pulmonary angiography requires that the contrast be injected distal to the pulmonary valve with the right heart ejecting.

PCPS flow rates appear to result in much better systemic support compared to other devices, such as the intraaortic balloon pump. The intraaortic balloon pump can only increase cardiac output by about 20% and is of no value in patients in cardiac arrest. This may be particularly important during transport from the catheterization laboratory to the operating room. Cardiopulmonary bypass support also differs from other available circulatory support systems

(Table 9-3), which include the hemopump, left atrial-femoral artery bypass, coronary sinus retroperfusion, and antegrade coronary perfusion catheters. The hemopump can be used to support high-risk intervention procedures, but has required surgical cutdown and placement across the aortic valve and thus is not practical during cardiac arrest with resuscitation in progress. Left atrial to femoral bypass support can be used in these circumstances, but requires transseptal catheterization, which is not practical during cardiopulmonary resuscitation. Also, not every physician is familiar with the technique of transseptal catheterization. Nonetheless, both of these devices can be used for prolonged periods.

Myocardial perfusion, either retrograde using the coronary sinus or antegrade, can provide direct myocardial perfusion in patients who have sustained cardiac arrest due to abrupt closure, but this is not practical in patients with severe hypotension or those in cardiac arrest. Following the institution of cardiopulmonary bypass support, however, myocardial perfusion may prove to be an important adjunct in limiting myocardial damage.

Our study, and others, have demonstrated the capability of PCPS to provide hemodynamic support in patients in cardiac arrest. The effectiveness of the support can be estimated by both the restoration of blood pressure and the maintenance of adequate tissue perfusion demonstrated by mixed venous O_2 saturation >69% in all patients in our series. Results are satisfactory only if PCPS is implemented early, particularly in the cardiac catheterization laboratory. The duration of cardiac arrest is an important prognostic indicator, with 95% dying if cardiopulmonary resuscitation lasts more than 15 minutes [32]. While the study that we have performed [18] is not controlled, survival of 4 out of 7 patients (57%) suggests that PCPS improves survival when instituted using the technique reported here. Kanter [7] also reported a similar experience in six patients who survived. Overlie et al. [21] have also demonstrated improved survival if PCPS is instituted early, particularly in the catheterization laboratory. Most survivors in our study have undergone either coronary bypass graft surgery, angioplasty, or other procedures to correct the underlying problem. This is in contrast to previous studies using cardiopulmonary bypass support in which no revascularization was attempted. This suggests

Table 9-3. Available circulatory supports

REDUCING DEMAND (SYSTEMIC)
Intraaortic balloon pump
Left atrial-femoral bypass support
Hemopump
Percutaneous cardiopulmonary bypass support
Left ventricular assist devices
INCREASING SUPPLY (CORONARY)
Autoperfusion catheters
Retroperfusion (coronary sinus)

that the contribution of PCPS is to stabilize the patient in order to make a complete diagnosis and to provide support during definitive treatment. Survival also depends on whether the underlying disease is amenable to definitive therapy. In our experience, if PCPS is instituted in the catheterization laboratory within 20 minutes and the underlying problem is corrected either with surgery or with repeat angioplasty, the survival is >80%.

These are, however, disadvantages of PCPS, which include incomplete left ventricular unloading, ischemia in the distribution of an occluded vessel, and the inability to use it for prolonged periods. Also, significant iliofemoral disease precludes cannula placement in some patients.

As the use of cardiopulmonary bypass support is limited to only a few hours, serious ethical issues may arise regarding termination of life support in a patient with adequate cerebral function, but without adequate cardiac function. This may also expose cardiologists to difficult ethical issues. Case selection is, therefore, particularly important.

FUTURE DIRECTIONS

Many technological developments in the future may result in more survivors. In the future, rapidly primed systems and improvement in the cannulation procedure using smaller, low friction cannulae for rapid vascular access may lead to a further reduction in insertion time. Using a large amount of heparin in patients in an emergency situation has occasionally led to significant blood loss and a need exists to develop systems that do not need heparin. Myocardial preservation may be possible using either hypothermia and coronary perfusion with either autoperfusion catheters or active antegrade perfusion (under investigation), or perhaps ventricular unloading with evacuation of the left ventricle with a pigtail catheter.

Because of our experience in patients with early institution of PCPS in the catheterization laboratory, we believe that the survival is markedly improved if PCPS is instituted early and is followed by immediate treatment of the underlying problem. Because of the importance of rapid institution, the hospital must put into place procedures that allow rapid mobilization. Furthermore, it will be very difficult to use this device emergently with current technology unless the perfusionists, nursing personel, cardiologists, and cardiac surgeons are very familiar with the use of the device in elective cases. For physicians to try to apply these devices for the first time in an emergency situation, without having been trained in their use of these devices, could certainly be dangerous.

CONCLUSION

The development of percutaneous initiation of cardiopulmonry bypass support using femoral vessels provides an effective means of support in patients in cardiac arrest. PCPS can facilitate emergency revascularization by either angioplasty or bypass surgery in the setting of cardiac arrest. However, further studies will be necessary to define the exact role of PCPS, as well the role of

adjunctive therapy with techniques such as myocardial perfusion catheters, relative hypothermia, and left ventricular venting. The role of PCPS as a bridge to other left ventricular assist devices should be explored, particularly in patients in whom revascularization in not possible.

REFERENCES

1. Lande AJ, Edwards L, Bloch JH. Clinical experience with emergency use of prolonged cardiopulmonary bypass with a membrane oxygenator. *Ann Thorac Surg* 1970; 10:409–423.
2. Lefamine A, Harken D. Extracorporal support of the circulation by means of venoarterial bypass with an oxygenator. *J Thorac Cardiovasc Surg* 1971; 62:769–780.
3. Yankovsky V, Lanovenko I. Hemodynamic changes during reeanimation after prolonged clinical death cauased by blood loss. *Resuscitation* 1972; 1:311–325.
4. McDonnel MA, Kralios AC, Tsagaris TJ. Comparative effect of counterpulsation and bypass on left ventricular myocardial oxygen consumption and dynamics before and after coronary occlusion. *Am Heart J* 1979; 97:78–88.
5. Laas J, Campbell CD, Takanasi Y. Effectiveness and limitation of intra-aortic balloon counterpulsation in myocardial infarction in swine. *Br J Surg* 1979; 66:883–884.
6. Takanashi Y, Campbell CD, Laas J. Reduction of myocardial infarct size in swine: A comparative study of intra-aortic balloon pumping and transapical left ventricular bypass. *Ann Thorac Surg* 1981; 32:475–485.
7. Kantor KR, Pennington G, Vandormael M, et al. Emergency resuscitation with extracorporeal membrane oxygenation for failed angioplasty (abstr). *J Am Coll Cardiol* 1988; 11:149.
8. Shawl FA, Domanski MJ, Wish MH, Davis M. Percutaneous cardiopulmonary bypass support in the catheterization laboratory: Technique and complications. *J Am Coll Cardiol* 1989; 13:159A.
9. Proctor E, Kowalik TA. Circulatory support by pump-oxygenator in experimental ventricular fibrillation and acute left heart failure induced by coronary artery ligation. *Cardiovasc Res* 1967; 1:189–193.
10. Evans D, Baird RJ. The effects of closed-chest venoarterial bypass with oxygenation on cardiopulmonary hemodynamics. *J Thorac Cardiovasc Surgery* 1971; 62:76–82.
11. Bricker DL, Kennedy JH. Criteria for selection of patients for mechanical circulatory support. *Am J Cardiol* 1971; 27:33–39.
12. Baird RJ, de la Rocha AG, Miyagishima RT. Assisted circulation following myocardial infarction: A review of 25 patients treated before 1971. *Can Med Assoc J* 1972; 107:287–291.
13. Mattox KL, Beall AC. Application of portable cardiopulmonary bypass. *JACEP* 1975; 4:528–531.
14. Phillips S, Ballentine B, Slonine D. Percutaneous initiation of cardiopulmonary bypass. *Ann Thorac Surg* 1983; 36:223–225.
15. Shawl FA, Domanski MJ, Wish MH, Davis M. Percutaneous cardiopulmonary bypass support in the cathterization laboratory: Technique and complications 1990; 120:195–203.
16. Shawl FA, Domanski MJ, Punja S, Hernandez TJ. Percutaneous cardiopulmonary bypass support in high risk patients undergoing percutaneous transluminal coronry angioplasty. *Am J Cardiol* 1989; 64:1258–1263.
17. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Emergency percutaneous cardiopulmonary bypass with cardiogenic shock from acute myocardial infarction. *Am J Cardiol* 1989; 64:967–970.
18. Shawl FA, Domanski MJ, Wish MH, Davis M, Punja S, Hernandez TJ. Emergency cardiopulmonary bypass support in patients with cardiac arrest in the catheterization laboratory. *Cathet Cardiovasc Diag* 1990; 19:8–32.
19. Shawl FA, Domanski MJ, Yackee JM, Wish MH, Dullam M, Neimat S. Left ventricular rupture complicating percutaneous mitral commissurotomy: Salvage using percutaneous cardiopulmonary bypass support. In press.
20. Shawl FA. Percutaneous cardiopulmonary bypass support in high risk interventions. *J Invas Cardiol* 1989; 5:287–293.
21. Overlie PA, Reichman RT, Smith SC. Emergency use of portable cardiopulmonary bypass in patients with cardiac arrest (abstr). *J Am Coll Cardiol* 1989; 13:160A.

22. Cowley MJ, Dorros G, Kelsey SF, Van Raden M, Detre KM. Emergency coronary bypass surgery after coronary angioplasty: The National Heart, Lung, and Blood Institute's Percutaneous Transluminal Coronary Angioplasty Registry experience. *Am J Cardiol* 1984; 53:22C–26C.
23. Bredlau CE, Roubin GS, Leimgruber PP, Douglas JS Jr., King SB III, Gruentzig AR. In-hospital morbidity and mortality in patients undergoing elective coronary angioplasty. *Circulation* 1985; 72:1044–1052.
24. Holmes DR. Comparison of complication during percutaneous transluminal coronary angioplasty from 1977 to 1981 and from 1985 to 1986. *J Am Coll Cardiol* 1988; 12:1149.
25. Sinclair IN, et al. Predictors, therapeutic options and long-term outcome of abrupt reclosure. *Am J Cardiol* 1988; 61:61G.
26. Emory University Cardiovascular Data Bank, unpublished data.
27. Reichman RT, Joyo CI, Dembitsky WP, et al. Improved patient survival after cardiac arrest using a cardiopulmonary support system. *Ann Thorac Surg* 1990; 49:101–105.
28. Lown B. Cardiovascular collapse and sudden cardiac death. In Braunwald E, ed, *Heart Disease. A Textbook of Cardiovascular Medicine*, 2nd ed. W.B. Saunders, Philadelphia, 1984, pp. 774–806.
29. Kouwenhoven WB, Jude JR, Knikerbocker GG. Closed chest cardiac massage. *JAMA* 1960; 173:1064–1067.
30. Austen WG, Buckley MJ, Mundth ED, Sanders CA. Assisted circulation: Intra-aortic balloon pumping. *Translplant Proc* 1971; 3:1474.
31. American Heart Association. Standards and guidelines for cardiopulmonary resuscitation (CPR) and emergency cardiac care (ECC). *JAMA* 1980; 244:462–468.
32. Bedell SE, Delbanco TL, Cook EF, et al. Survival after cardiopulmonary resuscitation in the hospital. *N Engl J Med* 1983; 309:569–608.
33. Wexler HR, Gelb AW. Controversies in cardiopulmonary resuscitation. *Crit Care Clin* 1986; 2:335–348.
34. Gibbon JH Jr. Artificial maintenance of circulation during experimental occlusion of pulmonary artery. *Arch Surg* 1937, 34:1105.
35. Goldman A, Boszormaenyi E, Utsu F, et al. Veno-arterial pulsatile partial bypass for circulatory assist. *Dis Chest* 1966; 50:633–640.
36. Bregman D, Casarella WJ. Percutaneous intra-aortic balloon pumping: Initial clinical experience. *Ann Thorac Surg* 1979; 29:153–155.
37. Scheidt S, Wilmur G, Mueller H, et al. Intra-aortic balloon counterpulsation in cardiogenic shock. *N Engl J Med* 1973; 43:979–984.

10. DECISION MAKING DURING FEMORO-FEMORAL VENO-ARTERIAL CARDIOPULMONARY BYPASS IN THE CARDIAC CATHETERIZATION LABORATORY

A. KENNETH LITZIE

INTRODUCTION

The availability of full-flow portable femoro-femoral cardiopulmonary bypass support (CPS™ System, C.R. Bard, Inc., Tewksbury, MA) has changed the current practice of interventional cardiology in many medical centers throughout the United States, Canada, and Europe. This newly refined technology is applied electively and prophylactically in the catheterization laboratory and has also been used outside the catheterization laboratory for emergencies, including circulatory and respiratory support for patients suffering from pulmonary embolus, exposure hypothermia, and shock.

As outlined below, a variety of topics necessary for the safe and effective conduct of CPS bypass will be reviewed and discussed in this chapter:

1. Preparation for CPS (room, patient, system)
2. Initiating CPS
3. Managing CPS
4. Arterial blood gas control
5. Troubleshooting

PREPARATION FOR CPS BYPASS

After a patient has been selected as a candidate for femoro-femoral cardiopulmonary bypass (CPS) but before initiating bypass, prepatory procedures are conducted to ensure the safety and efficacy of the procedure. Such pro-

cedures can be divided into three general categories: those related to room preparation, those related to patient preparation, and those concerning perfusion apparatus preparation.

The room

Many catheterization laboratories are well configured for supporting a CPS bypass program. In other catheterization laboratories, there may be several areas in which the characteristics of the room will need to be evaluated and modified as necessary to conform to the needs of the perfusion equipment.

Some femoro-femoral cardiopulmonary bypass (FF-CPB) systems require a 20-amp AC power source. This may necessitate new electrical wiring of the catheterization laboratory to avoid a potential circuit overload and resultant power interruption. Investigation by the hospital biomedical department may be indicated because FF-CPB systems requiring 20-amp service have special electric plugs that will not fit into a typical AC wall receptacle.

Space limitations are not usually a problem because currently available FF-CPB systems only utilize 4–6 sq ft of floor space. Situations requiring movement of the FF-CPB equipment during a procedure may occur when the catheterization table is moved to accommodate fluoroscopy or cine angiography. Wires, tubings, and other obstructions should be removed to ensure the free movement of the bypass apparatus when necessary.

Battery-powered lighting or the installation of "spot" lights may be necessary so that the perfusionist can see the control console and the bypass equipment.

Another physical plant issue concerns access to medical-grade dry oxygen and air. Both of these compressed gases are routinely used during CPS bypass procedures. Large cylinders of air and oxygen in the catheterization laboratory may suffice, but standard, flush-mounted, centrally sourced gases are more practical because they do not occupy floor space, and gas supply line routing to the perfusion circuit can be optimized.

Just as for patients undergoing cardiopulmonary bypass for cardiac surgery, patients supported with CPS bypass in the catheterization laboratory at times require pharmacologic contol of vascuar tone and the level of consciousness. In addition, systemic anticoagulation with heparin sodium (approximately 300 IU/kg) may be indicated [1]. Appropriate agents in adequate volumes should be routinely available.

To facilitate the manipulation of extracorporeal tubings in the sterile field, instruments, such as heavy-duty scissors and tubing clamps, are often indicated. If the femoral cannulae are to be inserted surgically rather than percutaneously, the typical spectrum of surgical instrumentation will be necessary. If the cannulae are inserted percutaneously, extreme caution should be excercised in avoiding the possibility of cannulae (arterial cannula in particular) migration out of the vascular space. Arterial cannula could become extravascular, yet remain subcutaneous and result in significant and precipitous loss of circula-

tory blood volume. It is possible that sutures may be necessary to ensure cannulae security. Additional equipment and materials should include an appropriate anticoagulation monitor (activated clotting time [ACT] monitor most typically), as well as the associated disposable blood tubes.

There are several standard solutions used to prime the extracorporeal circuit. These are typically not i.v. solutions used for parenteral administration, but solutions specifically formulated as priming solutions for extracorporeal circuits. In addition, blood should be made available, as cardiopulmonary bypass and full systemic anticoagulation may create a need for blood transfusion. As experience with CPS increases, actual utilization of blood decreases dramatically to near zero.

Should a suboptimal procedure outcome occur requiring patient transport to another location (usually surgery), the transportation corridor should be able to accommodate both the patient bed and the perfusion hardware. Additional support personnel will also be present, occasionally rendering a traditional route impassable. Corridors, doorways, and elevators should be tested in a mock transfer to ensure that a proposed path is suitable. Access to, and ready availability of, an elevator key to urgently summon an elevator can also be advantageous.

A review of the areas in which the catheterization laboratory should be evaluated in terms of its suitability for accomodating CPS bypass procedures follows in Table 10-1.

The Patient

Prudent use of leg and torso safety straps will discourage the patient from flexing at the groin. This is important because flexing at the groin while on CPS bypass can result in the abrupt and complete interruption of circulatory support secondary to "kinked" femoral cannulae.

Everyday use of nasal prongs for the administration of oxygen is not routinely required, but could prove advantageous under certain circumstances. During periods of partial circulatory support with CPS (defined as those times during which the patient and the extracorporeal circuit share responsibility for total systemic blood flow), the patient's pulmonary circulation is solely responsible for controlling the blood gases of the patient-generated cardiac output [2]. The presence or absence of patient-generated cardiac output is determined by the pulsitility of the arterial pressure waveform. The presence of pulsitility indicates persistent cardiac ejection (indicating the possibility of

Table 10-1. Catheterization laboratory preparation for CPS bypass

AC power	Medications
Bedside space	Instrumentation
Lighting	IV solutions/blood products
Medical-grade gas sources	Transportation corridor

substantial pulmonary blood flow) and warrants careful monitoring of the adequacy of the patient's cephalad perfusion.

This issue requires attention due to the often observed moderate to profound depression in the patient's respiratory rate while being supported with CPS bypass. This depression in respiratory rate is not of significant concern, except if the patient is unconscious. The adequacy of cerebral perfusion in conscious patients, even those with depressed respiratory rates, can be assessed qualitatively through verbal interaction with the patient.

Because verbal interaction is not an option for the unconscious patient, another mechanism to determine the adequacy of oxygenation in aortic arch blood must be employed. At least two different mechanisms have been utilized to monitor this parameter. The use of pulse oxymetry on the patient's right side (in the brachiocephalic distribution, furthest away from femoral bypass arterial return [3]) can be used as a trend monitor. For more accurate analysis of arch gases, right radial artery blood gases provide a convenient and utilitarian (continuous systemic pressure monitoring) access route. Those patients who are unconscious and who are not breathing spontaneously must be ventilated mechanically by an endotracheal tube or mask, and have serial or continuous assessments made of aortic arch blood gases.

The femoro-femoral cardiopulmonary bypass system

The FF-CPB system should be assembled, primed, and otherwise readied according to the manufacturer's instructions for use. Procedures will vary from one manufacturer to another, however, several common operational techniques will apply equally to each. Operation of the CPS system will be discussed below and outlined in Table 10-2.

Following placement of the perfusion circuit on the CPS cart and testing the heat exchanger for leaks, priming is initiated by passive filling of the circuit with an appropriate solution. Simultaneously, the perfusionist connects the oxygen supply line, the pressure monitoring line, the blood flow meter, and the blood temperature probe to the appropriate perfusion circuit components. Upon completion of the passive prime, the CPS system is recirculated at a

Table 10-2. CPS system priming checklist (abbreviated)

1. Check heat exchanger for leaks
2. Gravity prime the perfusion circuit
3. Connect oxygen line, flow probe, temperature probe
4. Connect pressure monitoring line
5. Recirculate at 10 l/min to remove air
6. Purge sample and pressure monitoring ports
7. Stop recirculation and examine circuit for air
8. Calibrate blood flow meter
9. Set pump speed and clamp transfusion lines
10. Assess air safety of all central venous lines

high flow rate (10 l/min) until all air remaining in the circuit has been filtered out through the membrane oxygenator.

Standard cardiopulmonary bypass in the operating room routinely utilizes an arterial line filter to trap air in the arterial circuit. Arterial line filters are impractical in the setting of urgent circulatory support, and therefore other means of air removal must be applied. When evaluating FF-CPB circuits for suitability in the catheterization laboratory, the ability to filter air should be of paramount importance.

A nonocclusive blood pump is the pump of choice for CPS bypass because it is autoregulatory. These pumps are typically referred to as centrifugal or constrained vortex pumps [1]. The laws of physics dictate that a planar body of fluid accelerated into a circular path generates a region of low pressure perpendicular to its plane of rotation and a region of high pressure around the greatest radius of rotation. By orienting a fluid inlet port along the low-pressure axis of the rotating body of fluid and an outlet port tangentially aligned with the high-pressure pathway, fluid flow is accomplished without the hazards associated with the use of positive displacement pumps. Such hazards include inflow pressure insensitivity, outflow pressure insensitivity, indiscriminant pumping of air intraarterially, and a slightly greater tendency to damage formed blood elements. Avoidance of all of these hazards is necessary for the safe conduct of CPS bypass.

Redundancy in all safety features, especially those where air can threaten the integrity of the perfusion circuit, is necessary. Areas of particular concern include the junction between the femoral venous cannula and the perfusion circuit; the priming/transfusion lines; and any containers open to the atmosphere, such as venous or cardiotomy reservoirs. Special note should be taken of any deep central venous lines. If open to the atmosphere through a manometer or gravity-fed intravenous line, the very low central venous pressures possible during full-flow CPS bypass could entrain air through those conduits into the right heart and perfusion circuit. As a precautionary routine, all deep central venous lines should be examined for air safety before the initiation of cardiopulmonary bypass. Specific practices include the use of transducers on physiologic monitoring lines and volumetric infusion devices on drug administration lines. Under no circumstances should a central venous access procedure be conducted during CPS bypass until and unless there are unambiguous signs of significantly positive central venous pressures. Even then, extreme caution should be employed to avoid entrainment of air through an introducer, dilator, or sheath into the central venous circulation and extracorporeal circuit.

If not already performed, the perfusion circuit and hardware assembly should be examined, by checklist, for readiness. This should include a final inspection of the perfusion circuit to ensure the absence of air; suitable perfusate temperature; a clotting time analysis to verify adequate patient anticoagulation; a confirmation of the appropiateness of the rate of delivery, and

composition of oxygenator and patient ventilating gases; a determination regarding the sufficiency of compressed oxygen and air sources; and a check of the backup battery power charge and function.

INITIATING CPS BYPASS

Introduction

A review of the blood flow pathways in a patient on femoro-femoral cardiopulmonary bypass is appropriate at this time to illustrate how it differs from normal circulation and standard cardiopulmonary bypass. The route described below is descriptive of the CPS system, but is representative of other FF-CPB circuits being considered for clinical use.

Venous blood is aspirated out of the patient's right atrium through a thin-wall 18 Fr venous cannula. The venous cannula is typically inserted into the femoral vein and is advanced through the inferior vena cave until the cannula tip rests inside the right atrium. Venous blood is conducted through the venous cannula, into the venous line, and then into a nonocclusive blood pump. The pump then propels blood through a heat exchanger and a high-efficiency oxygenator/bubble trap before returning it to the patient through a thin-wall femoral artery cannula. This type of arterial cannulation results in retrograde blood flow through the entire length of the aorta. Retrograde aortic blood flow has been used extensively in the past [4] for circulatory support during cardiac and major vascular surgical procedures. Tissue perfusion, however, always occurs in the normal antegrade direction.

The CPS circuit is significantly different in configuration and operation than typical cardiopulmonary bypass circuits. Among the most significant differences are the direct-aspiration means of removing blood from the right atrium and the closed or isovolemic nature of the blood conduit. Both of these characteristics are advantageous to the conduct of perfusion, especially in the cardiac catheterization laboratory. The direct-aspiration means of removing blood from the right atrium gives the pump operator discretionary control over the patient's cardiac preload and extracorporeal blood flow rate. (Inadequate blood flow rates are typical of gravity or siphon drainage FF-CPB systems.) The isovolemic nature of the circuitry eliminates any intravascular volume shift from the patient to the extracorporeal circuit. Since the perfusion circuit has no capacitive reservoir, each milliliter of venous blood aspirated out of the right atrium is replaced with a milliliter of blood returned to the patient via the femoral artery. Both of these features simplify the conduct of perfusion, increase the margin of safety, and make the procedure more efficacious than had previously been possible.

Going on bypass

The first step to initiate femoro-femoral bypass with an isovolemic, or closed, perfusion circuit involves unclamping the venous line. This gives the blood

pump access to the patient's venous blood volume. Opening the arterial line clamp creates a continuous conduit between the patient and the perfusion circuit. [It is important to appreciate that once both the venous and arterial line clamps are open, only the speed of the nonocclusive blood pump prevents the perfusion circuit from becoming large arterio-venous shunt. This would occur if the patient's arterial pressure was greater than the pressure generated by the blood pump. If arterio-venous (retrograde) flow is noticed upon initiation of bypass, increasing the speed of the blood pump to overcome the patient's arterial pressure will resolve the retrograde flow and commence normal antegrade veno-arterial flow.] Once antegrade blood flow is established, bypass can be instituted in the manner best suited to the patient's condition. For example, if the patient was in refractory cardiac arrest of short duration where "full-flow" bypass was desired, the CPS operator would increase the speed of the nonocclusive blood pump until one of the two following conditions was satisfied: a) a further increase in speed would not create a concomitant increase in blood flow or b) the perfusion lines, draped between the patient and the CPS hardware, began to "chatter." Either of these two phenomena indicate that, under the existing conditions, further increases in blood flow will **not** be achieved by only increasing blood pump speed (Table 10-3).

Alternately, for a "supported angioplasty" patient, for instance, the physician often selects an extracorporeal blood flow rate less than that which would be required on "full-flow" bypass, but still affords the patient relief from angina and ischemic ECG changes during percutaneous transluminal coronary angioplasty (PTCA) balloon inflation. Indices used as targets for this application include average blood flow rates of between 2 and 4 l/min and pulmonary artery pressures <5 mmHg with normal systemic blood pressures and patient mentation. Being fully aware of the hemodynamic parameters that are manifest during "partial" CPS bypass is necessary and will be discussed in detail later in this chapter.

MANAGING CPS BYPASS

Except under urgent circumstances, CPS bypass should be initiated in the cardiac catheterization laboratory more slowly than in the operating room in fully obtunded patients. This will reduce the transient, but at times severe, nausea and flushing occasionally seen during precipitous initiation of CPS bypass in

Table 10-3. Maximum initial blood flow rate indices

Observation	Cause
1. Increase pump speed; no increase in QB	No blood available in right atrium
2. Perfusion lines "chatter"	Soft tissues of IVC & RA intermittently collapsing over venous cannula

conscious patients. Persistent, moderate diaphoresis is common in this setting and has been attributed to increased blood flow during normothermic assisted circulation, and to a lower than baseline systemic vascular resistance, causing significant improvements in cutaneous perfusion.

After initiating CPS bypass, the first two clinical parameters that must be assessed are blood flow and blood pressure. Which parameter is optimized first is usually dependent upon the clinical circumstances. When using CPS as a resuscitative tool, blood flow is often the first priority, while during elective CPS use, adequate blood pressure control is the most important parameter [5]. Pressure control during elective, prophylactic circulatory support, currently the most frequent application for CPS bypass [6], will be discussed first.

Pressure control — Full-flow CPS bypass

When a patient is placed on full-flow CPS bypass as a prophylactic circulatory support measure, systemic blood pressure is usually the first hemodynamic parameter to be optimized. Systemic blood pressure on cardiopulmonary bypass is assessed through the use of the mean arterial pressure (MAP). MAP is affected by patient-generated cardiac output (CO), extracorporeal blood flow rate (QB), systemic vascular resistance (SVR), and central venous pressure (CVP). During full-flow CPS bypass, when patient-generated CO is absent, the MAP is related to the parameters mentioned above, as specified in the following equation:

$$\frac{\text{MAP} - \text{CVP}}{\text{QB}} \times 80 = \text{SVR}.$$

It can be seen that mean arterial pressure is proportional to the product of SVR and QB. Therefore, if blood flow is kept constant at the level necessary to meet the patient's respiratory and metabolic demands, MAP may be controlled by adjusting SVR with suitable vasoactive agents. Typically, these agents are not beta-agonists, and therefore, should not increase myocardial oxygen demand [7].

In addition to mean arterial pressure control, perfusion gradient is another parameter that should be optimized. The perfusion pressure gradient can be defined as the difference between the MAP and the CVP (MAP − CVP). For seriously ill cardiac patients not on bypass, maximizing the perfusion pressure gradient could be accomplished by increasing the mean arterial pressure. However, that option results in an increase in myocardial work and myocardial oxygen consumption secondary to an increase in afterload, and results in a decrease in cardiac output.

An alternate approach for patients not on bypass would be to reduce cardiac preload (CVP). However, *both* the mean arterial pressure *and* the cardiac output fall if CVP is reduced beyond a certain threshold. On CPS bypass, it is possible to maximize the perfusion pressure gradient (MAP − CVP), not only

by maintaining mean arterial pressure within a normal range, but by reducing central venous pressure below that which would otherwise be possible. This approach is possible because CPS gives the operator the ability to *aspirate* blood out of the right atrium until cardiac preload, or CVP, is at or near zero while maintaining normal or supernormal systemic blood flow rates. Gravity-fed or siphon drainage type femoro-femoral cardiopulmonary bypass systems without this capability cannot completely evacuate the right atrium.

Pressure Control — Partial CPS Bypass

In the case of prophylactic partial bypass, after the predetermined or symptomatically indicated extracorporeal blood flow rate is achieved, the patient's mean arterial pressure is maintained by the interaction of the patient's systemic vascular resistance and *both* the native cardiac output *and* the extracorporeal blood flow rate, as illustrated in Table 10-4.

Because the patient's contribution to total systemic blood flow cannot be assessed by traditional thermodilution or dye dilution methods, nor can the central venous pressure be reliably measured while on bypass, the actual systemic vascular resistance will be difficult to determine. In circumstances where the patient's mean arterial pressure is higher or lower than desired, the medical staff must assess whether SVR, patient-generated cardiac output, or extracorporeal blood flow rate should be adjusted. Which of these singlely or cumulatively will exert the desired effect on MAP will be affected by individual patient-to-patient variability.

As an example of how important a full understanding of bypass hemodynamics is during CPS bypass, a hypothetical case study follows. The purpose of this example is to demonstrate how a typical patient with coronary artery disease undergoing PTCA could manifest either of the following clinical presentations during CPS bypass, depending upon the specific nature and extent of the patient's disease state.

Scenario 1. Hemodynamically stable

The venous line clamp is removed first, followed by the arterial line clamp and a concomitant increase in blood pump RPM to a total blood flow of 0.5 LPM. Approximately 30 seconds later, RPM are increased to achieve a blood flow of 1.0 LPM. This process is continued while closely observing the patient's hemodynamic pressures for adequacy. As the extracorporeal blood flow rate

Table 10-4. MAP and SVR on partial CPS bypass

$$\frac{MAP - CVP}{QB + CO} \times 80 = SVR$$

or

$$MAP \propto SVR \times (QB + CO)$$

is increased, the patient's cardiac preload decreases, as does patient-generated cardiac output. At an extracorporeal blood flow rate of 3.0 LPM, the patient's MAP, SvO_2, urine output, and sensorium are intact; the arterial waveform is sinosoidal; and the stage is set for a high risk PTCA or valvuloplasty.

Scenario 2. Hemodynamically unstable

All proceeds as described above up to the point (for purposes of this example) that the blood flow rate is adjusted above 1.0 LPM. Immediately upon increasing the blood flow rate above 1.0, the concomitant decrease in cardiac preload creates a profound reduction in patient-generated cardiac output. A relatively minor reduction of cardiac preload below a threshold that cannot be prepoeratively defined can result in a total systemic blood flow well below that which is necessary to maintain adequate perfusion pressure. Swift correction of this situation is mandatory to avoid prolonged hypoperfusion and the resultant cascade of ischemic complications. Corrective actions could include transfusion, increasing pump speed to achieve full-flow CPS bypass, or reducing the extracorporeal blood flow rate to allow the intrinsic cardiac preload and patient-generated cardiac output to increase.

Blood flow rate control — Full-flow CPS bypass

Since patients placed on full-flow CPS bypass under emergency circumstances usually have no intrinsic cardiac output, the extracorporeal blood flow rate is usually the first hemodynamic parameter to be optimized. The adequacy of oxygen delivery is best determined by monitoring the venous blood oxygen saturation because of the direct relationship venous oxygen saturation has systemic blood flow rate. Calculating oxygen transfer involves determining the patient's hemoglobin concentration and blood flow rate, and measuring the difference in oxygen saturation between arterial and venous blood (Table 10-5) [1].

Because arterial oxygen saturation is essentially 100% and hemoglobin concentration is assumed to remain constant, oxygen consumption is a function of only one variable, SvO_2.

Although ill-advised, the tendency to utilize blood flow rate as a primary mechanism for systemic pressure control is pervasive. Only under circumstances similar to those described above in Scenario 2 should blood flow be the principal mechanism through which blood pressure is controlled.

Table 10-5. Venous oxygen saturation — Index of blood flow adeqacy

$(SaO_2 - SvO_2) \times (Hgb \times 1.34) \times 10 \times QB = Oxygen\ consumption,$
where: Hgb = hemoglobin concentration (g/dl); SaO_2 = arterial oxygen saturation (decimal form); SvO_2 = venous oxygen saturation (decimal form); QB = systemic blood flow rate (liters/minute).

As discussed earlier, blood pressure regulation in the presence of adequate blood flow rates is a direct function of systemic vascular resistance.

To reinforce the importance of utilizing venous oxygen saturation as the measure of adequacy for total systemic blood flow rate, a numerical example follows:

Under normal conditions about 30% (100% − 70%) of the oxygen contained in arterial blood is extracted through the process of nutritive perfusion after one circulatory cycle. If we assume that the patient's oxygen consumption is constant, and if the blood flow rate is inadequate, exemplified here as a blood flow rate of only 3.33 LPM, then venous oxygen saturation will be diagnostic of that inadequacy, demonstrating a saturation of only 55%, significantly less than the ideal venous oxygen saturation of approximately 70% (Table 10-6). Clearly, an increase in blood flow rate will deliver more fully saturated hemoglobin to tissue capillary beds, thus requiring less oxygen extraction per aliquot, resulting in an increase in venous oxygen saturation. Since the converse is also true, the CPS bypass operator has a powerful tool to assess and control the adequacy of oxygen delivery to the patient's tissues.

To review the basic rules of blood flow control during full-flow CPS bypass in the absence of any other complicating factors, increasing blood flow to treat a low venous oxygen saturation, and under some circumstances decreasing blood flow to correct high venous oxygen saturation levels, would be appropriate (Table 10-7).

Blood flow rate control — Partial bypass

The picture is complicated somewhat when a patient is on partial CPS bypass. This is because total systemic blood flow is the *sum* of the patient-generated antegrade cardiac output flow (CO) and the extracorporeal circuit blood flow (QB). Under these circumstances, arterial blood oxygenation occurs both in the patient's lungs and in the extracorporeal oxygenator. During partial bypass, the adequacy of cephalad perfusion (possibly supplied by patient-generated cardiac output) and caudad perfusion (supported by extracorporeal

Table 10-6. Relationship between SvO_2 and QB

$(SaO_2 - SvO_2) \times (Hgb \times 1.34) \times 10 \times QB = O_2$ consumption
$(1.0 - 0.70) \times 15\,g/dl \times 1.34\,ml/g \times 10 \times 5.0\,LPM = 301\,ml/min$
$(1.0 - 0.55) \times 15\,g/dl \times 1.34\,ml/g \times 10 \times 3.33\,LPM = 301\,ml/min$

Table 10-7. Adequacy of blood flow

Observation	Corrective action
Low SvO_2	Increase blood flow
High SvO_2	Reduce blood flow

blood flow) must be assessed independently. Assessment involves drawing arterial samples for blood gas analyses, both from the extracorporeal circuit and from the patient's aortic arch. The later sample is best drawn from the right radial artery as its connection to the aortic arch via the brachiocephalic artery is the sample site most distant from the CPS bypass femoral arterial return [8].

If the blood gases so drawn are disparate in their values, adjustments to the ventilating gas mixture of the artificial lung in the extracorporeal circuit will alter the blood gas composition serving the caudad circulation, while modifications of the patient ventilator settings will change the respiratory gas content of the patient-generated cardiac output.

As mentioned earlier, all unconscious patients on CPS bypass must, if not respiring spontaneously, be mechanically ventilated. This is necessary to ensure that the patient-generated cardiac output is adequately oxygenated. In a conscious patient, where spontaneous respirations may be significantly depressed, verbal interaction with the patient can be used as a gauge to assess the adequacy of cerebral perfusion.

Myocardial oxygen consumption

Reduction of myocardial oxygen consumption is a frequently misunderstood aspect of CPS bypass. Properly performed, CPS bypass can substantially reduce MVO_2. Clinical indices of such reduction are routinely observed as a resolution of angina pectoris and restoration toward the isoelectric of ischemic ST-segment changes. Appreciating the hemodynamics of MVO_2 reduction with CPS bypass revolves around two of the basic components of myocardial work — preload and afterload [7]. CPS bypass can minimize both of these parameters when employed as a full-flow circulatory support device. Even as a partial bypass support technique, such as that employed by Shawl and others during "supported angioplasty" procedures [9], MVO_2 can be reduced to the point where symptomatic myocardial ischemia induced during PTCA balloon inflation is relieved.

Whenever possible, the use of clinical indices, such as angina, ischemic ECG changes, and abnormal hemodynamic values, should be used as factors to guide the clinician toward optimizing all perfusion variables affecting myocardial work.

Cardiac preload during isovolemic CPS bypass is reduced in direct proportion to the speed of the blood pump. Because of the absence of a capacitive reservoir between the right atrial cannula and the blood pump, active aspiration results in a direct relationship between right atrial pressure (RAP) and extracorporeal blood flow rate. Increasing blood pump speed increases the extracorporeal blood flow rate, decreases RAP, and results in a reduction of MVO_2. That decrease in MVO_2, however, can be reversed if another major component determining myocardial oxygen consumption is ignored — afterload.

Since extracorporeal blood flow during partial CPS bypass is nonpulsatile,

normal patient-generated pulse pressures are reduced. As a rule, minimally pulsatile or nonpulsatile systemic arterial blood flow is not associated with any clinically significant physiologic or rheologic sequalae when employed within the manufacturer's guidelines. However, if a patient's MAP remains constant while the pulse pressure is reduced, along with a reduction in peak systolic pressure, a relative increase in aortic end-diastolic pressure may occur. To the extent that any increase in aortic end-diastolic pressure (true afterload) is *not* compensated by reductions in other parameters affecting myocardial oxygen consumption, MVO_2 could increase on CPS bypass.

It is recommended that for patients in whom myocardial oxygen consumption is a pressing concern, mean arterial pressures be controlled in a low-normal range (except for patients with severe carotid artery disease or other factors predisposing them to high systemic arterial pressures) and maximal preload reduction be achieved to maximize perfusion pressure gradients. This procedure is performed by increasing the speed of the blood pump, which simultaneously reduces cardiac preload and maintains systemic blood flow rates. Once preload is maximally reduced, systemic pressures (including aortic end-diastolic pressure) are adjusted with appropriate vasoactive agents.

Left ventricular venting options

Though numerous anecdotal reports have verified biventricular unloading during full-flow CPS bypass, it has been suggested that left ventricular (LV) distention requires serious attention because of its impact on subendocardial perfusion and myocardial oxygen consumption.

There exist several strategies for helping to ensure that left ventricular distention does not occur during CPS bypass. The first is to continuously observe a pulsatile waveform on the arterial trace. If the ventricle is still ejecting, it is unlikely that pathologic distention is present. However, in the absence of any evidence to the contrary in a patient with a functional cardiac rhythm, if no ejection is suggested by the arterial waveform, the physician will not know if the left ventricle is not ejecting because it is fully decompressed, or because it is overdistended.

Tests for LV distention in the absence of a pulsatile waveform are somewhat limited. For patients with perfusing cardiac rhythms, reducing systemic blood pressure (specifically aortic end-diastolic pressure), either temporarily or for the duration of the procedure, will increase the level of confidence that LV distention is absent. This procedure can only be performed in patients who can tolerate the reduced systemic pressures. The rationale for this approach is founded in the observation that, in the presence of a functional cardiac rhythm, a reduced afterload increases cardiac output by decreasing the isovolemic pressure threshold.

For patients with no functional cardiac rhythm, such as in those in refractory ventricular fibrillation, observations of complete biventricular decompression after extended periods of CPS circulatory support suggest triple-valve incom-

petence (mitral, pulmonic, and tricuspid) and left ventricular decompression by retrograde flow through the pulmonary vasculature to the extracorporeal venous cannula. Since this retrograde venting process is difficult to document in the clinical setting, a variety of other techniques have evolved to help ensure adequate LV decompression. These techniques include active pulmonary artery venting, active transvalvular (aortic) venting, and intermittent external chest compressions. Fortunately, persistent nonperfusing rhythms appear to be exceptional in the presence of normalized systemic blood flows and perfusion pressures during CPS bypass, the majority of them converting spontaneously, or with minimal defibrillatory effort, to perfusing rhythms.

ARTERIAL BLOOD GAS CONTROL

The most widely used artificial lungs, or oxygenators, are of the "membrane" type. These oxygenators interpose a gas-permeable membrane material between the patient's blood and the ventilating gas, very much as the pulmonary alveolar membrane separates blood from atmospheric air. Arterial pCO_2 is controlled by altering oxygenator ventilating gas flow rate in the same manner as would be expected as the minute volume of a standard ventilator is changed, that is, as the ventilating gas flow rate is increased, it reduces arterial pCO_2. The rate at which CO_2 is removed is directly proportional to the gas flow rate, and therefore the arterial pCO_2 is inversely proportional to the gas flow rate. Carbon dioxide is driven through the membrane material by the diffusion gradient caused by the relatively high concentration of carbon dioxide in the blood relative to its concentration in the ventilating gas.

Utilizing the same analogy, when adjusting a mechanical ventilator to increase a patient's arterial pO_2, the fractional percent of oxygen in the ventilating gas (FiO_2) is varied. The magnitude and direction of changes in the extracorporeal oxygenator ventilating gas FiO_2 is mirrored by proportional changes in arterial pO_2.

To review these concepts, refer to Table 10-8 and the associated expanded descriptions.

1. Elevated pCO_2 may be caused by inappropriately low ventilating gas to blood flow ratio, unexpectedly high CO_2 production by the patient, or occasionally by an oxygenator run for an excessively long period of time.

Table 10-8. Blood gas control

Condition	Correction
1. High pCO_2	Increase gas flow rate
2. Low pCO_2	Decrease gas flow rate
3. High pO_2	Decrease FiO_2
4. Low pO_2	Increase FiO_2

In the presence of elevated pCO_2, an increase in the ventilating gas flow rate will reduce arterial pCO_2.

2. Low pCO_2 is usually caused by an excessively high ventilating gas to blood flow ratio or, very rarely, a low CO_2 production rate by the patient (most typically found in hypothermic patients). If pCO_2 values are unacceptably low, reducing ventilating gas flow rate will allow blood CO_2 concentrations to rise. Notice that, in general terms, there is an inverse relationship between blood pCO_2 values and gas flow rate.
3. High arterial oxygen tensions are often found when ventilating the extracorporeal oxygenator with 100% oxygen or when the patient is hypothermic. To adjust unacceptably high pO_2 values, blend filtered dry air into the ventilating gas to reduce FiO_2. (Note: Air to be used in membrane oxygenators only).
4. Unusually low arterial pO_2 levels are usually seen in circumstances where there is an inadequate blood flow rate or the oxygen concentration in the ventilating gas is too low. If low pO_2 is due to an inadequate blood flow rate (accompanied by low venous oxygen saturations), the corrective action is to increase the systemic blood flow rate. Under most other circumstances, increasing the percent oxygen in the ventilating gas will allow blood oxygen concentrations to rise. Notice that, in general terms, there is a direct relationship between FiO_2 and arterial pO_2.

It is important to note that these techniques apply *only* to the blood that is passing through the extracorporeal circuit. Only in patients on full flow CPS bypass do the remedies suggested above hold true for the sum total of the patient's systemic blood flow, for only in those patients does the CPS bypass process all their blood through the extracorporeal oxygenator.

This is a very different circumstance than partial bypass, where persistent cardiac ejections indicate blood is being pumped through the patient's lungs, into the left ventricle and then into the aortic arch. The importance of *continuous* pulmonary ventilation for CPS bypass patients should be emphasized. As mentioned previously, to assess aortic arch blood gases, right radial artery samples should be drawn and appropriate changes made to the patient's ventilator settings based on that analysis.

TROUBLESHOOTING

Pressure control

Once a patient is on CPS bypass, cardiac preload, mean arterial pressure, aortic end-diastolic pressure, and systemic perfusion pressure gradient all become controllable parameters. Through the coordinated adjustments of blood flow rates and systemic vascular resistance, all of these parameters can be optimized to best address the patients underlying pathology. It should be remembered that calculating SVR during full-flow bypass is straightforward, since the value for total systemic blood flow is known to be equal to the extracorporeal

Table 10-9. Hypotension

Observation	Corrective action
Adequate blood flow Low arterial pressure Low systemic vascular resistance	Increase SVR

or pump flow rate. This is in contrast performing the SVR calculation while on partial CPS bypass, during which time the magnitude of patient-generated cardiac output is unobtainable. Even in the absence of quantitative indices, Table 10-9 describes general recommendations that are typically applicable for patients who are hypotensive in the presence of adequate systemic blood flow.

In the presence of what is thought to be an adequate blood flow rate (as determined by venous oxygen saturations or target blood flow rates), a low arterial pressure, and low systemic vascular resistance, the use of alpha-adrenergic agents to increase vascular tone, without inotropic or chronotropic cardiac stimulation, may be indicated.

Conversely, if blood flow is thought to be adequate, but systemic blood pressure and systemic vascular resistance are high, vasodilator therapy should be considered (Table 10-10).

Hypoperfusion

It should be noted that during an actual CPS bypass procedure, it may not be possible to achieve a high enough blood flow rate to satisfy the patient's oxygen requirements, which would be manifested as a venous oxygen saturation significantly below 70%. This problem is usually attributable to 1 of these 4 primary causes: kinked cannula or partially clamped line, poor cannula position, cannula entrapment, hypovolemia. The mechanics of each of these problems will be addressed individually and appropriate remedies will be suggested below.

Mechanical obstruction

One potential cause for limited access to blood flow is the presence of some physical compromise in the blood flow pathway through the extracorporeal circuit. This cause of limited blood flow is checked by examining the CPS

Table 10-10. Hypertension

Observation	Corrective action
Adequate blood flow High arterial pressure High systemic vascular resistance	Decrease SVR

bypass circuit "from cannula to cannula" and correcting any conditions that compromise the lumen of circuit components. These conditions could include kinked blood lines, cannulae, or incompletely released line clamps.

Venous cannula position

Another possible cause of limited blood flow resulting in unacceptably low venous oxygen saturation levels and inadequate circulatory support is related to venous cannula position. Ideally, the tip of the venous cannula will be located in the middle to lower portion of the patient's right atrium. If the patient maintains a significantly pulsatile arterial waveform while on full-flow CPS bypass, the venous cannula should be *carefully* repositioned to optimize venous drainage.

NOTE: It is important that the position of the arterial cannula *never* be adjusted without the guidewire and dilator/introducer in place.

Venous cannula entrapment

Occasionally, poor blood flow rates can be attributed to venous cannula entrapment. If the speed of the blood pump is disproportionately high relative to the volume of venous return, the drainage holes in the venous cannula may have become occluded by the soft tissues of the right atrium or vena cavae. To correct this situation, reduce the speed of the blood pump by at least half to release the soft tissues, then slowly increase until a rise in pump speed is not accompanied by an augmentation of blood flow or until an adequate blood flow rate is achieved.

Hypovolemia

The most common reason for less than optimal blood flow on CPS bypass (assuming proper equipment and cannulae) is hypovolemia. Hypovolemia, relative to CPS bypass, means that an inadequate volume of blood is available in the area of the right atrium to support normal blood flows. Specifically, hypovolemia presents in at least three forms, each of which requires a distinct therapeutic response.

1. Loss of body fluid, e.g., hemorrhage, dehydration
2. Peripheral pooling, e.g., shock, low SVR
3. Vascular leak, e.g., edema, third spacing

Discriminating between these forms of hypovolemia, and the most appropriate therapies to correct them in an effort to establish adequate blood flows on bypass, requires sound clinical judgment. The specifics will vary from patient to patient, but in general terms, the first line of therapy to items 1–3 above might consist of transfusion, vasoconstriction, and osmotic/oncotic plasma expansion therapies, respectively.

Hypervolemia

Under some circumstances, blood flow rates in excess of what the patient requires may be obtainable. This would be reflected in normothermic venous oxygen saturations that exceed 70% by some significant margin. Although clinically rare, such situations are sometimes encountered when CPS bypass is used as a resuscitative tool after an extended CPR procedure or in patients with significant cardiac chamber enlargement. There is no patient advantage to exposing the blood to additional unnecessary passes through the extracorporeal circuit. Excess veno-arterial blood flow rates can usually be attributed to hypervolemia.

If the CPS bypass blood flow rate were to be reduced to a blood flow rate lower than that which was maximally obtainable, blood returning to the right atrium in excess of that CPS bypass flow rate would function as a cardiac preload and result in a patient on bypass, yet still ejecting. For cardiac patients, in whom maximal reduction of myocardial oxygen consumption may be indicated, the persistent ejections caused by excess blood volume remaining in the right atrium will create additional work and a relative increase in myocardial oxygen consumption compared to that possible if the myocardium was fully decompressed. Under such circumstances, one or more of the following techniques can be used to reduce intravascular and right atrial volume during CPS bypass.

Phlebotomy

Phlebotomize the patient by attaching a suitable container, such as a blood transfer pack, to an appropriate extracorporeal blood supply line. Care should be taken to adhere to aseptic technique and to avoid inadvertent introduction of air into the extracorporeal circuit or the patient. Removal of the blood volume in excess of that required to support adequate systemic blood flow rates on bypass will optimally reduce cardiac preload and should thereby decrease myocardial oxygen consumption.

Cell Saving

Alternately, by attaching a large bore Luer-lock extension assembly from a blood supply line to a mechanical cell concentration device, excess asanguinous volume can be removed while simultaneously increasing circulating hemoglobin concentration and achieving the desired reduction in circulating volume and cardiac preload.

Hemoconcentration

If there is no urgency regarding the reduction of right atrial volume, an in-line hemoconcentration device can be attached to a blood supply line. The patient's intravascular volume can then be reduced while increasing hemoglobin concentrations on a continuous basis, rather than in a batch mode which is typical of a cell saving apparatus.

Alternatively, systemic approaches to reducing right atrial volumes on CPS

Table 10-11. Transporting patients on CPS bypass

1. Patient and perfusion lines
   Make sure that the patient is secure on the transport bed and the perfusion lines are firmly attached to the patient.
   [NOTE: For patients not respiring spontaneously, a means for mechanically ventilating the patient must be available.]
2. Strain relief
   A method to avoid any strain on the perfusion lines is necessary to protect the integrity of the femoral cannulation site.
3. Battery pack charge
   The status of the battery pack charge must be checked to determine if enough energy remains in the battery to run the blood pump during transport.
4. Oxygen supply
   An adequate portable oxygen supply must be confirmed prior to transporting the patient.
5. Miscellaneous supplies
   Other supplies, such as i.v. solutions, syringes, medications, blood pump, hand crank, and monitoring equipment should be readied for transport before the CPS system is disconnected from the AC power source.

bypass, such as diuresis or vasodilation, can be used. The choice of any of these possible therapeutic alternatives is based on the entire clinical scenario.

Preparing for transport or power failure

Preparing to transport a patient on CPS bypass can be made a comfortable and safe procedure if all the requirements and contingencies for such a transport

Table 10-12. CPS versus open heart (OH) procedures

CPS	OH
Typically not O.R.	Only done in O.R.
Conscious patient	Unconscious patient
Restraints/pain	Obtunded/paralyzed
Unique heparin protocol	Standard heparin protocol
Continuous pt. ventilation	Ventilation not necessary
Percutaneous cannulation	Surgical cannulation
Femoral arterial cannulation	Aortic arch cannulation
Distal limb perfusion	Not applicable
Femoral venous cannulation	Right atrial cannulation
Gradual bypass initiation	Rapid bypass initiation
Normothermia	Hypothermia
Diaphoresis/nausea	No patient reaction
Direct aspiration drainage	Gravity (siphon) drainage
Central venous line liability	Little if any liability
Isovolemic perfusion	Capacitive perfusion circ
RPM = 1/CVP	No relation between RPM & CVP
Partial-/full-flow bypass	Full-flow bypass
Arch ABG analyses separate	Circuit ABG adequate
SVR for BP control	QB for BP control
QB for SVO_2 control	Anesthesia/flow for SVO_2
Nonstandard hemodynamics	Standard hemodynamic
Weaning — preload & SVR	Transfusion
Percutaneous closure	Surgical closure
Two-day recovery	Five-day recovery

are anticipated. Table 10-11 lists a few of the general categories in which preparations should be made. A detailed clinical protocol is mandatory for all centers anticipating the initiation of a CPS bypass program. The protocol should include not only the general information regarding patient selection criteria and data collection, but also detailed treatments of exceptional circumstances, such as patient transport to the operating room, patient transport from another facility by ground or air, elective use of CPS bypass in the operating room, and use of CPS bypass for resuscitation.

Operating room

Utilizing a CPS bypass system in the operating room can greatly facilitate a surgical procedure, or turn a routine case in one of exceptionally high complexity and stress. There are many substantive differences in the operation and capabilities of CPS bypass systems when compared to full cardiopulmonary bypass circuits (Table 10-12). Yet, for specific applications, FF-CPB is finding its way back into the operating room for procedures as routine as thoracic and thoraco-abdominal aneurysms and redo cardiac surgical operations.

Four major areas need to be considered before CPS bypass can be safely and effectively applied in the surgical suite. Those areas are

1. Air safety
2. Circulatory volume management
3. Shed blood scavenging
4. Access for blood cardioplegia.

The cardiac surgical and perfusion teams should evaluate these areas to determine the best methods by which each can be addressed. Open consultation with all members of the medical, surgical, and perfusion staff is the best assurance of a productive and profitable CPS bypass program.

REFERENCES

1. Reed CC, Stafford JB, eds. *Cardiopulmonary Bypass*, 2nd ed. Medical Press, Houston, 1985.
2. Guyton AC. *Guyton's Textbook of Medical Physiology*, 6th ed. W.B. Saunders Philadelphia, 1981.
3. Austin JW, Harner DL. *The Heart-Lung Machine and Related Technologies of Open-Heart Surgery*. Phoenix Medical Communication Medical Publishers, Phoenix, AZ, 1986.
4. Galletti PM, Breacher GA. *Heart-Lung Bypass: Principles & Techniques of Extracorporeal Circulation*. Gruen & Stratton, New York, 1962.
5. Berne RM, Levy MN. *Cardiovascular Physiology*, 2nd ed. C.V. Mosby St. Louis, 1972.
6. Vogel RA, Shawl FA. Initial report of the National Registry of Elective Cardiopulmonary Bypass Supported Coronary Angioplasty. *J Am Coll Cardiol* 1990; 15(1):23–29.
7. Quaal S. *Comprehensive Intraaortic Balloon Pumping*. C.V. Mosby, St. Louis, 1984.
8. Ansar BJ. *An Atlas of Human Anatomy*. W.B. Saunders, Philadelphia, 1963.
9. Shawl FA. Percutaneous CardioPulmonary Support (PCPS) in High Risk PTCA, Cardiogenic Shock and Cardiac Arrest, Revised Protocol. Nov. 1989, Washington Adventist Hosp., Takoma Park, MD 20912.

SECTION III

11. INTRAAORTIC BALLOON PUMP SUPPORTED HIGH RISK CORONARY ANGIOPLASTY

MARC H. WISH AND FAYAZ A. SHAWL

INTRODUCTION

Since the first clinical report of the use of intraaortic balloon counterpulsation in 1967 [1], this technique has been used to support critically ill patients in a variety of settings. It is an accepted and widely used tool available to the invasive cardiologist. Percutaneous insertion [2,3] increased the practicality of the technique by making insertion more rapid and by removing the need for a surgical cutdown. Balloon pumping is most often used to treat cardiogenic shock, postoperative left ventricular dysfunction, unstable angina, and post-infarction angina. More recently, balloon pumping has also been used in "high risk" patients undergoing coronary angioplasty. This chapter will address the indications and use of the intraaortic balloon pump and review its role in supporting high risk patients during angioplasty.

EVOLUTION OF INTRAAORTIC BALLOON COUNTERPULSATION

The concept of providing diastolic augmentation in pressure by counterpulsation was initially described in 1953 by Kantrowitz [4]. In 1961, a balloon pump placed in the aorta over a catheter was described by Clauss et al. [5]. In 1962, Moulopoulos et al. [6] demonstrated the effectiveness of the intraaortic balloon in dogs. In 1967, Kantrowitz [7] reported intraaortic balloon placement in 27 cardiogenic shock patients. Results were good, with reversal of the shock state in some of the patients. In 1970, Buckley et al. [8] demonstrated that balloon

inflation during diastole improves coronary perfusion by reducing left ventricular wall tension and increasing diastolic coronary perfusion.

In the last 20 years, there have been many articles describing the hemodynamic effects of balloon counterpulsation and reports of its use in various clinical states. Percutaneous placement of the balloon catheter was described in 1980 [2]. Placement of the balloon catheter over a guidewire simplified matters further [3]. Smaller and smaller diameter balloon catheters were developed, and sizes as small as 8.5 and 9.5 Fr (compared to the previously used 12 Fr) are now available. While it was hoped that reduction in size would result in a lower incidence of vascular complications, this, unfortunately, has not occurred [9–12].

HEMODYNAMICS OF INTRAAORTIC BALLOON PUMPING

Balloon counterpulsation is a two-step process [5,6,13]. First, the balloon expands at end systole or as the aortic valve closes. The displacement of blood in the aorta increases diastolic aortic pressure (diastolic augmentation). This inflation must be timed to occur at the dicrotic notch in arterial pressure tracing. Inflation that occurs too early will result in inappropriately timed closure of the aortic valve with a decrease in stroke volume.

The second phase of the balloon pumping cycle involves the rapid deflation of the balloon just prior to the next systole. This rapid withdrawal of gas volume from the balloon causes a decrease in aortic blood volume, which results in reduced afterload. As a result of this afterload reduction, stroke volume and cardiac performance are improved.

The timing of inflation and deflation are critical to the balloon's performance. The pumps that are available time inflation and deflation using the electrocardiogram, but visual inspection and correction of the timing of augmentation using an arterial pressure tracing is essential.

A good electrocardiographic signal is needed for timing the balloon pump. The pump works best in association with normal sinus rhythm. Nonsinus rhythms, such as atrial fibrillation, affect the quality of diastolic and systolic augmentation, because the interval between ventricular complexes varies and the duration of diastole is not constant. When the rate of sinus tachycardia exceeds 120 bpm, decreased gas flow and volume reduces the augmentation [14]. At faster rates or during atrial fibrillation, reduction in augmentation from 1:1 to 1:2 or 1:3 may, in fact, provide better hemodynamics.

Balloon counterpulsation has been reported by many to improve cardiac performance and to reduce myocardial oxygen demand [15]. For this reason, it makes a great deal of sense in the treatment of ischemic states. There is a reduction in systolic blood pressure and left ventricular end-diastolic pressure of about 10–15% [16–18], and this may further reduce myocardial oxygen demand.

The reduction in preload has the effect of improving the clinical manisfestations of heart failure. Improved oxygenation results from lower pulmonary

arterial pressures, and improved forward flow, which may increase diuresis and improve tissue perfusion. Cardiac output increases of 10–40% have been reported [16,19]. Hemodynamic improvement usually diminishes over several days [17,20].

There is doubt as to whether balloon pumping actually improves coronary blood flow despite an increase in aortic diastolic pressure. Improved blood flow to ischemic areas has been reported in dogs with experimental ischemia and balloon pumping [21,22], but there have been studies to the contrary in dogs [23], and human data are also contradictory [24,25]. In one canine infarct model, the balloon pump was shown to improve coronary blood flow despite the loss of autoregulation of coronary flow present during an infarct [26].

EQUIPMENT AND TECHNIQUE

The equipment involved consists of the balloon catheter itself and the control console. The balloon catheters available come in adult and pediatric sizes. A 40-ml balloon, common in adult use, has a diameter of 18 mm. Balloons as small as 8.5 Fr are available for adult use, though without a central lumen at this size. It can be inserted either percutaneously over a guidewire or through cutdown on the femoral artery.

The pumping console consists of the electronics for monitoring and triggering, power source, and gas storage. The gas is either carbon dioxide (soluble in the event of leak, though not used anymore) or helium (its small molecular weight allows rapid movement of gas and it is inert). The electronic control system should allow for evaluation of inflation and deflation timing by showing an arterial pressure tracing and electrocardiogram. Other features available include markers that indicate the exact timing of inflation and deflation, strip-chart recorders, the ability to time using pacemaker rhythms, the pumping rate (1:1 to as little as 1:8), less augmentation than the full volume of the balloon, and a selection of signals to trigger from (such as ECG or arterial tracing). Consoles should also provide internal controls and alarms for detected gas leakage or loss of a waveform to trigger from.

We insert 40 cc intraaortic balloons percutaneously over a guidewire from the femoral artery and position the tip by fluoroscopy just distal to the origin of the left subclavian artery. Then 1:1 counterpulsation is begun. The patients are fully heparinized, with partial thromboplastin times of 80 ± 10 seconds. When used in conjunction with a cardiac catheterization or angioplasty, the balloon is deflated while catheters or guidewires are passed through the descending aorta, but are otherwise actively pumping throughout the procedures.

INDICATIONS AND CLINICAL EXPERIENCE WITH THE INTRAAORTIC BALLOON PUMP

Since the initial reports on the use of the intraaortic balloon pump (IABP) in patients with cardiogenic shock accompanying acute myocardial infarction, the indications for IABP have expanded.

Kantrowitz [1] demonstrated improved hemodynamics in his group of patients with cardiogenic shock and acute myocardial infarction, and others have reported improvement in the hypotension and low-output state of this group [17,27]. The short-term survival rates, however, remained about 25% [19,28–30]. Using the IABP for myocardial infarction complicated by heart failure has not been shown to decrease infarct size or mortality [31]. Thus, the IABP should be thought of as a temporizing measure, and not a treatment in and of itself. Patients in whom balloon pumping is performed in conjunction with coronary angiography and prompt corrective procedures have an improved prognosis [17,32,33].

The IABP has become used most frequently postoperatively in many institutions [17,29,32]. Following bypass surgery, some patients have a low-output state, despite the use of inotropic drugs. Before the balloon pump, mortality in this group was high, but balloon pumping has reduced the mortality by about 50% [17,34].

The IABP has also been used in unstable angina refractory to medical therapy. As with heart failure, it is a temporizing measure only, which stabilizes the patient awaiting definitive therapy. Its use in unstable angina has decreased in the past decade, because of the introduction of intravenous nitroglycerin and new antianginals, such as the calcium-channel blockers.

The IABP has been used to maintain hemodynamic stability in patients with left ventricular dysfunction or coronary disease undergoing surgery. Bolooki [17], in a retrospective analysis, has recommended criteria for prophylactic use. These include a low ejection fraction of <30%, left ventricular end-diastolic pressure >25 mmHg, and cardiac index <1.8 l/min/m^2. There has been no randomized, controlled study of this use.

INTRAAORTIC BALLOON PUMP DURING HIGH RISK CORONARY ANGIOPLASTY

There have been several studies outlining the use of the IABP in the catherization lab in association with percutaneous transluminal coronary angioplasty (PTCA). Alcan et al. [35] in 1983, described 14 patients in whom the IABP was a useful adjunct in the catheterization lab. Four situations for balloon pumping were listed. The first was in cases in which PTCA might otherwise be considered contraindicated because of the otherwise clinically unstable condition of the patient. The second, in cases in which PTCA was unsuccessful, IABP allowed added preoperative stability and resulted in a smoother transition from the catheterization lab to the operating room. The third was patients who develop acute closure of a coronary artery during angioplasty who require emergency coronary bypass surgery. Finally is the case of patients who have a successful angioplasty, but experience acute closure during post-procedure observation. The IABP for these patients provides a smoother transition back to the catheterization lab or to the operating room. Of the 14 patients in this study, 13 survived hospitalization [36].

Murphy et al. [37], in 1984, reported 32 patients requiring emergency surgical revascularization after attempted angioplasty. Immediate insertion of a balloon pump was performed in 16 of these patients in the catheterization lab. One of the authors' conclusions is that immediate preoperative IABP is a useful adjunct to emergency revascularization. The use of the IABP during angioplasty for patients in cardiogenic shock [38] and as part of the preoperative therapy after failed angioplasty has been described by others [39].

The balloon pump has been used as an adjunct during PTCA, including that for left main coronary artery disease [40]. Voudris et al. [41] instituted IABP prophylactically in 27 patients considered to be at high risk for PTCA. Twenty-four of these patients had poor left ventricular function with an ejection fraction <40%, with a mean of 29 ± 10%, and PTCA was performed on the artery supplying most of the remaining viable myocardium. In another three patients, balloon pumping was instituted due to advanced age in patients with multivessel dilatation. There were no deaths, no myocardial infarctions, and no emergency bypass procedures. The follow-up period was 9–21 months. Since this was not a randomized study, it is unclear which of the patients required support. Only three had been deemed inoperable, only 13 had angina Class III or IV, and only 11 had three-vessel coronary disease. The mean ejection fraction was almost 30%, and only four had had prior bypass surgery.

Kahn et al. [42] recently reported further experience with the IABP in "high risk" coronary angioplasty. This population of 28 patients had a mean age of 66 years, with 10 over 70 years. Class III or Class IV angina was present in 82%, with a mean ejection fraction of 24% (89% with ejection fraction <30%). Three-vessel disease was present in 93% of the patients, and seven patients had left main disease. There were no deaths or infarctions within 72 hours of the procedure. Vascular complications occurred in three patients (11%). In 11 patients, systolic blood pressure fell to <70 mmHg, but the augmented remained over 90 mmHg. No acute occlusions were described, and dilatation was successful in 96% of vessels attempted. It is not stated how long blood pressure may have been under 70 mmHg systolic, nor how long the inflation times were. Also, their results describe experience within 72 hours of the initial PTCA, it is not clear if there were other cardiac events prior to hospital dishcarge. Whether similar results could be maintained in a large series remains to be seen.

Anwar et al. [43] recently described a two-center experience with the IABP for elective high-risk angioplasty. Ninety-seven patients with an ejection fraction <35% (26% of these with ejection fraction <26%) were evaluated. Angioplasty was successful in 85.6% of patients. Seven patients had unsuccessful angioplasty without a major event. However, seven patients suffered a major cardiac event, four required emergency bypass surgery with myocardial infarction, two had uneventful bypass surgery, and one died in the operating room following failed angioplasty. There were 20 late deaths.

This experience with IABP must be compared, however, to that of cardiopulmonary support for patients undergoing high risk angioplasty, which is described fully elsewhere in this book. It is the feeling of our group and others [44] that cardiopulmonary bypass support is an invaluable adjunct in the catheterization lab and is preferable to IABP for truly high-risk angioplasty. There is no way to predict the electromechanical dissociation that can occur in patients with a low ejection fraction undergoing angioplasty of a "last remaining" vessel. Though the lack of cardiac output could be reversible, an IABP cannot "assume the hemodynamic burden" that cardiopulmonary bypass support with high flows can [44]. In this recent study [44], cardiopulmonary bypass support also further extended balloon inflation times, from a mean of 113 seconds with the IABP to 172 seconds with bypass support. Prolonged inflation has been reported to decrease restenosis [45], and possibly to improve initial results, which may explain, in part, the improved symptomatic status and lower requirement for revascularization in patients undergoing bypass support versus IABP.

LIMITATIONS OF INTRAAORTIC BALLOON PUMPING

The IABP requires a stable ventricular rhythm. It is ineffective during ventricular tachycardia or fibrillation, asystole, or with extremely low blood pressure. The role of the IABP in high risk PTCA, particularly that of the last remaining vessel, is therefore questioned. What type of high risk patient may benefit from IABP support alone requires further study.

COMPLICATIONS OF BALLOON PUMPING

Complications occur frequently. Leg ischemia has been reported to occur in 10–33% of cases [9,10,30,32] and appears to be more common with the percutaneous approach [46]. Other factors associated with increased risk of ischemia include preexisting iliofemoral disease, urgency of placement, diabetes, and female gender [47].

Aortic dissection is uncommon [12,48] but may occur without being clinically evident [49]. Peripheral embolization is also uncommon but has been reported [12,50]. A nonaugmenting balloon presents a high risk for thrombus and embolization, and must be considered a medical emergency. Infections are uncommon but the risk is increased in obese and diabetic patients [51]. As with any vascular access, the chance of infection increases with time. Systemic infection occurs in about 1% of patients, with the local infection rate being several times higher [9].

Late complications include claudication, paresis, and pseudoaneurysm of the femoral artery [51]. Hemotologic complications of balloon pumping include thrombocytopenia and hemolytic anemia, which is caused by mechanical trauma to the blood. Although hematologic parameters should be closely monitored, significant problems are uncommon [52].

CONCLUSIONS

The IABP, first used clinically 23 years ago, has become the most widely used device for support of the failing heart. Its insertion has become simpler, and the indications for its use have grown. It can be used for days at a time, but is accompanied by a significant risk of vascular or infectious complications.

There is a definite role of the IABP in certain high risk patients undergoing interventional procedures in the catheterization laboratory. The population of patients who will benefit from the IABP, as opposed to cardiopulmonary bypass support, during high risk PTCA needs further study.

REFERENCES

1. Kantrowitz A, Tjonneland S, Freed PS, et al. Initial clinical experience with intraaortic balloon pumping in cardiogenic shock. *JAMA* 1968; 203:135.
2. Bregman D, Casarella WJ. Percutaneous intraaortic balloon pumping: Initial clinical experience. *Ann Thorac Surg* 1980; 29:153.
3. Subramanian VA, Goldstein JE, Sos TA, et al. Preliminary clinical experience with percutaneous intraaortic balloon pumping. *Circulation* 1980; 62(Suppl. I):123.
4. Kantrowitz A, Kantrowitz A: Experimental augmentation of coronary flow by retardation if the arterial pressure pulse. *Surgery* 1953; 34:678.
5. Clauss RH, Birtwell WC, Albertal G, et al. Assisted circulation. I. The artificial counterpulsator. *J Thorac Cardiovasc Surg* 1961; 41:447.
6. Moulopoulos SD, Topaz S, Kolff WJ. Diastolic balloon pumping (with carbon dioxide) in the aorta: Mechanical assistance to the failing circulation. *Am Heart J* 1962; 63:699.
7. Kantrowitz, Krakauer JS, Rosenbaum A, et al. Phase shift balloon pumping in medically refractory cardiogenic shock. Results in 27 patients. *Arch Surg* 1969; 99:739.
8. Buckley MJ, Leinbach RL, Kastor JA, et al. Hemodynamic evaluation of intraaortic balloon pumping in man. *Circulation* 1970; 41(Suppl. II):II-130.
9. Kantrowitz A, Wasfie T, Freed PS, et al. Intraaortic balloon pumping 1967 through 1982: Analysis of complication in 733 patients. *Am J Cardiol* 1986; 57:976.
10. Alpert J, Bhaktan EK, Gielchinsky I, et al. Vascular complications in intraaortic balloon pumping. *Arch Surg* 1976; 111:1190.
11. Sanfelippo PM, Baker NH, Ewy HG, et al. Vascular complications associated with the use of intraaortric balloon pumping. *Texas Heart Inst J* 1987; 14:178.
12. Gottlieb SO, Brinker JA, Borkon AM, et al. Identification of patients at high risk for complication of intraaortic balloon counterpulsation: A multivariate risk factor analysis. *Am J Cardiol* 1984; 53:1135.
13. Hahnloser PB, Gallo E, Schenk WG. Hemodynamics of counterpulsation. *J Thorac Cardiovasc Surg* 1966; 51:366.
14. ECRI. Evaluation: Intraaortic balloon pumps. *Health Devices* 1981; 11:3.
15. Parmley W, Chatterjee K, Charvuzi Y, et al. Hemodynamic effects of noninvasive systolic unloading (nitroprusside) and diastolic augmentation (external counterpulsation) in patients with acute myocardial infarction. *Am J Cardiol* 1974; 33:819.
16. Weber KT, Janicki JS. Intraaortic balloon counterpulsation: A review of physiological principles, clinical results, and device safety. *Ann Thorac Surg* 1974; 17:602.
17. Balooki H. Current status of circulatory support with an intraaortic balloon pump. *Cardiol Clin* 1985; 3(1):123.
18. Urschel CW, Eber L, Forrester J, et al. Alteration of mechanical performance of the ventricle by intraaortic balloon counterpulsation. *Am J Cardiol* 1970; 25:546.
19. Scheidt S, Wilner G, Mueller H, et al. Intraaortic balloon counterpulsation in cardiogenic shock: Report of a cooperative clinical trial. *N Engl J Med* 1973; 288:979.
20. Amsterdam EA, Awan NA, Lee G, et al. Intraaortic balloon counterpulsation: Rationale, application and results. *Cardiovasc Clin* 1981; 11:79.
21. Gill CC, Wechsler AS, Newman GE, et al. Augmentation of redistribution of myocardial

blood flow during acute ischemia by intraaortic balloon pumping. *Ann Thorac Surg* 1973; 16:445.
22. Sasayama S, Osakada G, Takahashi M, et al. Effects of intraaortic balloon counterpulsation on regional myocardial function during acute coronary occlusion in the dog. *Am J Cardiol* 1979; 43:59.
23. Shaw J, Taylor DR, Pitt B. Effects of intraaortic balloon counterpulsation on regional coronary blood flow in experimental myocardial infarction. *Am J Cardiol* 1974; 34:552.
24. Williams DO, Korr KS, Gewirtz H, et al. The effect of intraaortic balloon counterpulsation on regional myocardial blood flow and oxygen consumption in the presence of coronary artery stenosis in patients with unstable angina. *Circulation* 1982; 66:593.
25. Fuchs RM, Brin KP, Brinker JA, et al. Augmentation of regional coronary blood flow by intraaortic balloon counterpulsation in patients with unstable angina. *Circulation* 1983; 68:117.
26. Powell WJ Jr., Daggett WM, Magro AE, et al. Effects of intraaortic balloon counterpulsation on cardiac performance, oxygen consumption, and coronary blood flow in dogs. *Circ Res* 1970; 26:753.
27. Johnson SA, Scanlon PJ, Loeb HS, et al. Treatment of cardiogenic shock in myocardial infarction by intraaortic balloon counterpulsation surgery. *Am J Med* 1977; 62:687.
28. Ehrick DA, Biddle TL, Kronenberg MW, et al. The hemodynamic response to intraaortic balloon counterpulsation in patients with cardiogenic shock complication acute myocardial infarction. *Am Heart J* 1977; 93:274.
29. Goldberger M, Tabak SW, Shah PK. Clinical experience with intraaortic balloon counterpulsation in 112 consecutive patients. *Am Heart J* 1986; 111:497.
30. Alcan KE, Stertzer SH, Wallsh E, et al. Current status of intraaortic balloon counterpulsation in critical care cardiology. *Crit Care Med* 1984; 12:489.
31. O'Rourke MF, Norris RM, Campbell TJ, et al. Randomized controlled trial of intraaortic balloon counterpulsation in early myocardial infarction with acute heart failure. *Am J Cardiol* 1981; 47:815.
32. Sanfelippo PM, Baker NH, Ewy HG, et al. Experience with intraaortic balloon counterpulsation. *Ann Thorac Surg* 1986; 41:36.
33. Montoya A, McKeever L, Scanlon P, et al. Early repair of ventricular septal rupture after infarction. *Am J Cardiol* 1980; 45:345.
34. Buckley MJ, Craver JM, Gold HK, et al. Intraaortic balloon pump assist for cardiogenic shock after cardiopulmonary bypass (abstr). *Circulation* 1972; 46(II):76.
35. Alcan KE, Stertzer SH, Wallsh E, et al. The role of intraaortic balloon counterpulsation in patients undergoing percutaneous transluminal coronary angioplasty. *Am Heart J* 1983; 105:527.
36. Bolooki H. Emergency cardiac procedures in patients in cardiogenic shock due to complications of coronary artery disease. *Circulation* 1989; 79(Suppl. I):I137.
37. Murphy DA, Craver JM, Jones EL, et al. Surgical management of acute myocardial ischemia following percutaneous transluminal coronary angioplasty. Role of the intraaortic balloon pump. *J Thorac Cardiovasc Surg* 1984; 87:332.
38. Lee, Bates ER, Pitt B, et al. Percutaneous transluminal coronary angioplasty improves survival in acute myocardial infarction complicated by cardiogenic shock. *Circulation* 1988; 78:1345.
39. Talley JD, Jones EL, Weintraub WS, et al. Coronary artery bypass surgery after failed elective percutaneous transluminal coronary angioplasty. *Circulation* 1989; 79(Suppl. I):I126.
40. O'Keefe JH, Hartzler GO, Rutherford BD. Left main coronary angioplasty: Early and late results of 127 acute and elective procedures. *Am J Cardiol* 1989; 66:144.
41. Voudris V, Marco J, Morris MC, et al. Percutaneous transluminal coronary angioplasty with preventive intra-aortic balloon counterpulsation. *Cath Cardiovasc Diag* 1990; 19:160.
42. Kahn JK, Rutherford BD, McConahay DR, et al. Supported "high risk" coronary angioplasty using intraaortic balloon pump counterpulsation. *J Am Coll Cardiol* 1990; 15:1151.
43. Anwar A, Mooney M, Stertzer S, et al. Intra-aortic balloon counterpulsation support for elective coronary angioplasty in the setting of poor left ventricular function: A two center experience. *J Inv Cardiol* 1990; 2:175.
44. Stertzer SH, Myler RK. Left ventricular support during high risk coronary angioplasty: An argument for the use of cardiopulmonary support. *J Inv Cardiol* 1990; 2:155.
45. Kaltenbach M, Beyer J, Walter S, et al. Prolonged application of pressure in transluminal

coronary angioplasty. *Cathet Cardiovasc Diag* 1984; 10:213.
46. Goldberg MJ, Rubenfire M, Kantrowitz A, et al. Intraaortic balloon pump insertion: A randomized study comparing percutaneous and surgical techniques. *J Am Coll Cardiol* 1987; 9:515.
47. Alderman JD, Gabliani GI, McCabe CH, et al. Incidence and management of leg ischemia with percutaneous wire guided intraaortic balloon catheters. *J Am Coll Cardiol* 1987; 9:524.
48. McCabe JC, Abel RM, Subramanian VA, et al. Complication of intraaortic balloon insertion and counterpulsation. *Circulation* 1978; 57:769.
49. Isner JM, Cohen SR, Virmani R, et al. Complications of the intraaortic balloon counterpulsation device: Clinical and morphologic observation in 45 necropsy patients. *Am J Cardiol* 1980; 45:260.
50. McEnany MT, Kay HR, Buckley MJ, et al. Clinical experience with intraaortic balloon pump support in 728 patients. *Circulation* 1978; 58(Suppl. I):124.
51. Martin RS, Moncure AC, Buckley MJ, et al. Complications of percutaneous intraaortic balloon insertion. *J Thorac Cardiovasc Surg* 1983; 85:186.
52. Schneider MD, Kaye MP, Blatt SJ, et al. Safety of intraaortic balloon pumping. I. Biochemical and hematologic values influenced by use of balloon. *Thromb Res* 1974; 4:387.

12. MYOCARDIAL PROTECTION DURING CORONARY ANGIOPLASTY USING AUTOPERFUSION CATHETERS

ALAN N. TENAGLIA, E. MAGNUS OHMAN, AND RICHARD S. STACK

INTRODUCTION

Two major problems currently facing percutaneous transluminal coronary angioplasty (PTCA) are acute occlusion and late restenosis. As early as 1982, Kaltenbach et al. suggested that longer dilatations might improve the results of PTCA [1,2]. In 1988, Palazzo et al. reported on 26 patients who had unsuccessful PTCA using short inflation times (residual stenoses >50% in 15, acute occlusions in five, major dissections in six) in whom prolonged inflations of 1.5–15 minutes resulted in success in 23 of 27 lesions [3]. Theoretically prolonged and gradual expansions of the balloon might result in less trauma to the vessel, and less risk of a large dissection and acute occlusion. In addition, prolonged inflation might desiccate the plaque and by compressing nutrient flow to the vaso vasorum may decrease intimal hyperplasia.

However, the length of balloon inflation is limited by the resultant ischemia. Efforts to resolve this problem have included pharmacologic treatment with beta blockers, calcium-channel blockers, or nitrates, and attempts at perfusion using fluorocarbons, retrograde perfusion via the coronary sinus, or perfusion pump systems [4,5]. A very practical solution to the problem was the design of the autoperfusion balloon catheter, which utilizes side holes proximal and distal to the balloon to allow passive perfusion of blood during balloon inflation.

This chapter will first outline the development of the perfusion balloon catheter (PBC), including a discussion of both animal and initial human

studies. Next, we will describe the current model of the Stack Perfusion Dilatation Catheter™ (Advanced Cardiovascular Systems, Mountain View, CA) and the protocol for its use at Duke University Medical Center. Following this, the potential role of the PBC in four situations will be described: for routine PTCA, to salvage vessel patency in cases of failed PTCA, to allow dilatation of lesions that would otherwise be of too high risk for routine PTCA, and to maintain perfusion while arrangements are made for emergency coronary artery bypass grafting (CABG).

DEVELOPMENT AND ANIMAL STUDIES

In 1986, Erbel et al. in West Germany described a 3.7-mm balloon catheter (CPC catheter) that had two lumens [6]. One lumen was used for balloon inflation, while the second lumen contained holes both proximal and distal to the balloon to allow perfusion during balloon inflation. In five anesthetized open-chest dogs, the time to ischemia, as manifested by ECG, was determined with balloon inflation in the left anterior descending (LAD) artery, first using standard balloons and then using the CPC. In two dogs there was no change in time to ischemic ECG changes, but in the other three the time increased 30 to 180 seconds. These results are compromised by the phenomenon of myocardial "fading," which suggests that after one episode of ischemia it takes longer to reproduce ischemia with further occlusions.

In 1987, Turi et al. at Wayne State University described the use of an autoperfusion balloon catheter manufactured by United States Catheters Incorporated, which was a three-lumen, 4.3 Fr catheter with a 2.5 × 20 mm balloon [7,8]. The catheter contained eight side holes proximal and three side holes distal to the balloon, as well as an end hole. This catheter was also tested in anesthetized dogs. Random PTCA of the circumflex artery was performed using either the autoperfusion or standard balloon catheter. Inflations were performed for 3 minutes at 6 atm, and myocardial blood flow was determined by radioactive microspheres at 1 minute. In their study of 12 dogs, they found that the autoperfusion balloon inflations resulted in no ECG changes compared to an average ST elevation of 0.4 mV in the standard balloon group. Regional blood flow to the endocardium was 0.08 ml/min/g in the standard balloon group versus 0.61 ml/min/g in the autoperfusion balloon group.

Turi et al. have also reported on the use of their autoperfusion catheter in the left main coronary artery in a canine model [9]. In six dogs with 3-minute inflations with standard balloon catheters, 5 of 6 developed ventricular fibrillation, regional blood flow to the endocardiom was 0.08 ± 0.04 ml/min/g, and left ventricular systolic pressure dropped 85 ± 15 mmHg. With the use of the autoperfusion catheter, no dog developed ventricular fibrillation, regional blood flow was 0.63 ml/min/g, and systolic blood pressure only dropped by 8 mmHg. These results suggest that PTCA might be performed using an autoperfusion catheter in cases where standard PTCA would not be tolerated.

The Interventional Cardiovascular Program of Duke University Medical

Center has been very active in the area of autoperfusion catheter development [10]. In 1984, working in conjunction with Dr. John Simpson and Advanced Cardiovascular Systems, Inc. (ACS), a transluminal intracoronary reperfusion catheter was developed to maintain coronary perfusion during the period between failed PTCA and emergency coronary artery bypass grafting [11,12]. The device was a 4.3 Fr tapered tip catheter with 30 holes in a spiral pattern located in the distal 10 cm. The catheter was placed across an obstruction and blood entered the holes proximal to the obstruction and exited distally. In 20 patients with failed PTCA requiring emergency CABG, the reperfusion catheter was successfully placed across the obstruction in 18, with good antegrade flow in 16, associated with lessening of ST elevation and a decrease in chest pain. All of the patients with reestablished flow underwent successful surgery, with no deaths or significant cardiac complications. The conclusion was that the reperfusion catheter was a safe and effective means to reestablish and maintain coronary blood flow while preparations were made for emergency surgery. Ferguson et al. also showed that, in a series of eight patients at Duke, the use of the reperfusion catheter allowed more optimal surgery, permitting the use of internal mammary artery grafts in four of the patients [13]. Sundram et al. showed that in 31 patients requiring emergency CABG after failed PTCA, the use of a reperfusion catheter decreased the incidence of Q-wave myocardial infarction to 9% compared to 75% in patients treated with an intraaortic balloon pump [14].

Following this work, a balloon catheter that allowed perfusion during balloon inflation, the Stack Perfusion Dilatation Catheter, was developed. The initial catheter was a 4.5 Fr double-lumen polyethylene catheter with the central lumen open to linear side holes along the distal 10 cm with 10 holes proximal and 4 distal to the balloon [Figure 12-1]. Continuous perfusion is achieved by blood entering proximally, traveling through the lumen, and exiting distal to the balloon. An example of the use of the PBC in a patient with a significant lesion in the LAD is shown in Figure 12-2. In vitro flow rates, determined using 38% glycerol and a perfusion pressure of 80 mmHg, are shown in Table 12-1.

Animal studies showed that the PBC allowed prolonged balloon inflation with marked attenuation of ischemia due to the continued perfusion during

Table 12-1. *In-vitro* flow rates (cc/min) for the Stack PBC

	Inflation pressure			
Balloon size	0 psi	60 psi	90 psi	120 psi
2.5 mm	67.9	67.7	66.4	67.7
3.0 mm	65.4	65.2	64.0	63.5
3.5 mm	59.7	59.2	59.2	58.6

psi = pounds per square inch. From Stack RS et al. Perfusion balloon catheter. *Am J Cardiol* 1988; 61:77G–80G. With permission.

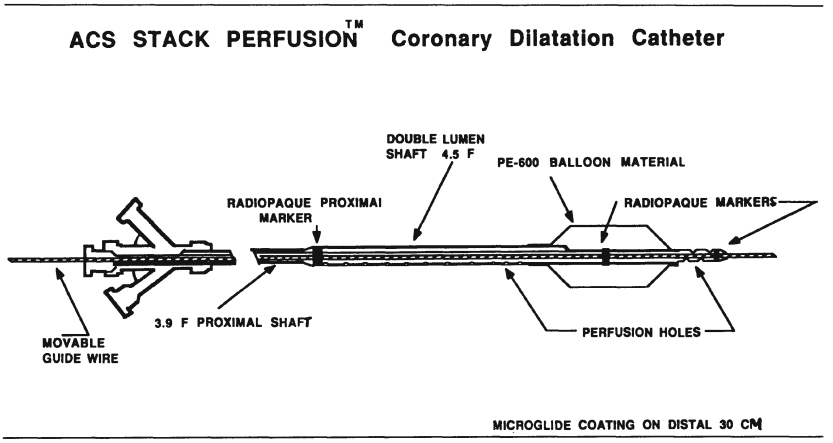

Figure 12-1. Stack Perfusion™ Dilatation catheter.

inflation [15,16]. In six dogs a standard Simpson Roberts™ balloon catheter was inflated in the coronary arteries for 3 minutes. ST elevation was noted in 5 of 6, ventricular arrhythmias in 5 of 6, and LV wall motion abnormalities in 6 of 6. In contrast, in five dogs using the PBC inflated for a mean of 37 minutes, none had ST elevation, arrhythmias, or wall motion abnormalities, and excellent distal perfusion was noted during balloon inflation (Table 12-2).

In studies [16] in six rabbits with bilateral iliac artery angioplasty using the PBC on one side inflated for 30 minutes at 9 atm compared to standard balloon on the other side inflated to 9 atm for 1 minute times 3, it was shown that the PBC resulted in decreased intimal, medial, and total thickness on pathologic examination of the arteries at 4 weeks (Figure 12-3).

Campbell et al. at Wayne State reported results in 21 dogs with circumflex artery occlusions using either standard or autoperfusion balloon catheter occlusions for 90 minutes [17]. They found ST elevation of 0.43 ± 0.13 mV

Table 12-2. PBC versus standard balloon inflation in dogs

	No. of dogs	Average inflation	ST-segment elevation	Ventricular arrhythmia	Left ventricular wall abnormality	Left ventricular ejection fraction
SRC	6[1]	3 ± 1 min	5/6	5/6	6/6	−22%
PBC	5	37 ± 10 min	0/5	0/5	0/5	7%

[1] One dog had ventricular fibrillation during SRC inflation and died before PBC insertion.
SRC = Simpson-Robert catheter; PBC = perfusion balloon catheter. From Stack RS et al. Perfusion balloon catheter. *Am J Cardiol* 1988; 61:77G–80G. With permission.

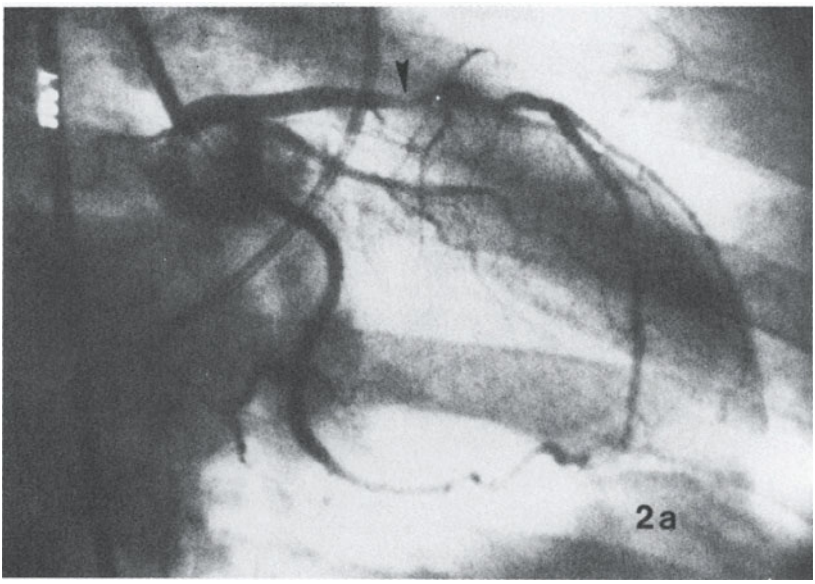

Figure 12-2A

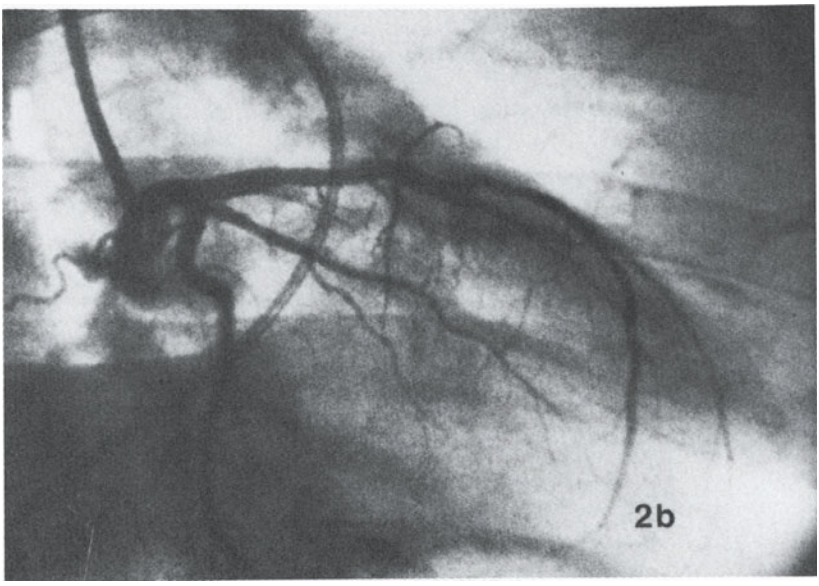

Figure 12-2B

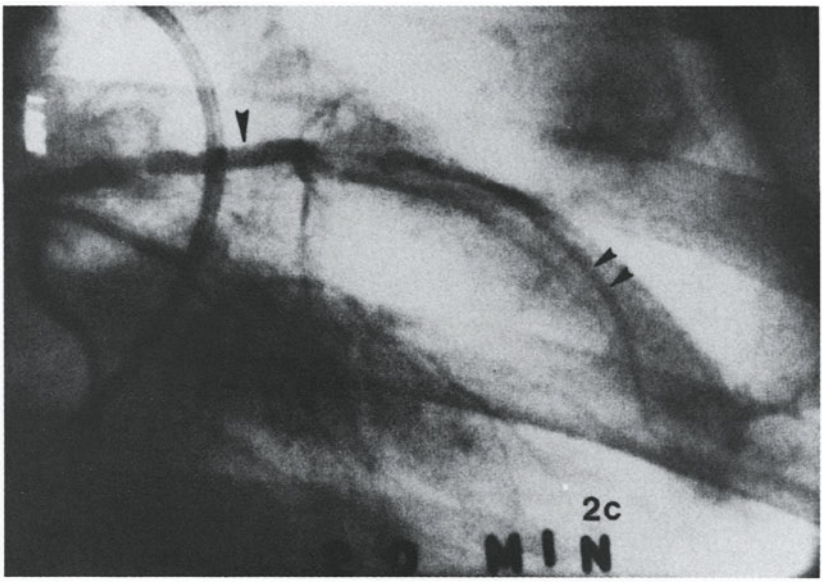

Figure 12-2C

Figure 12-2. Demonstration of the use of the Stack PBC. *a*: Significant lesion in LAD (arrow) prior to PTCA with PBC. *b*: Final result after PTCA. *c*: Arteriogram during PBC inflation showing position of PBC across lesion (large arrow) and good distal perfusion (small arrows). From Kereiakes DJ et al. Perfusion angioplasty. In: Topol EJ, ed. *Textbook of Interventional Cardiology*. W.B. Saunders, 1990, pp. 456–457. With permission.

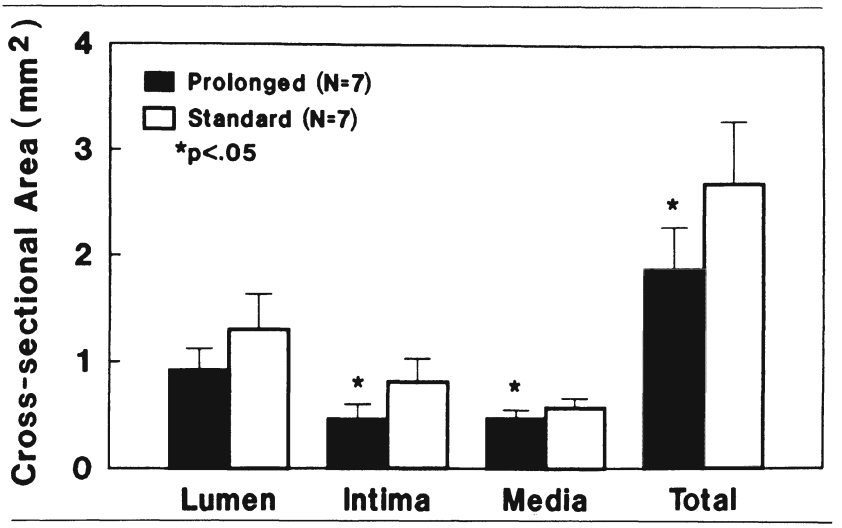

Figure 12-3. Prolonged versus standard balloon inflation in normal arteries. From Stack RS et al. Perfusion balloon catheter. *Am J Cardiol* 1988; 61:77G–80G. With permission.

in the standard group compared to -0.03 ± 0.03 in the autoperfusion group. Regional blood flow was 0.02 ± 0.01 ml/min/g versus 0.78 ± 0.27. Myocardial necrosis as a percentage of area at risk was $40.4 \pm 19.3\%$ versus $1.1 \pm 1.2\%$. They concluded that the autoperfusion catheter could maintain blood flow and limit myocardial ischemia and necrosis for as long as 90 minutes.

Zalewski et al. reported similar findings using the Stack PBC after LAD or circumflex occlusion in dogs but for as long as 6 hours of balloon inflation [18]. Again infarct area as a percentage of area at risk (as determined by labelled microspheres and triphenyltetrazolium staining) was reduced from $84 \pm 5\%$ to $25 \pm 9\%$ in the PBC group.

A recent study by Christensen et al. at University of Wisconsin showed that in dogs both the reperfusion catheter and the Stack PBC resulted in maintenance of regional myocardial blood flow throughout a period of 90 minutes of occlusion (0.72 ml/min for the reperfusion catheter, 0.63 ml/min for the PBC, and 0.14 ml/min in control animals) [19].

In summary, animal studies using autoperfusion catheters have shown that prolonged inflations are possible with attenuation or absence of ischemia, as documented by ST elevation on ECG, development of arrhythmias, or wall motion abnormalities. In addition, myocardial blood flow is maintained and myocardial necrosis is prevented.

HUMAN STUDIES

The initial use of the PBC in humans at Duke University Medical Center was in cases of failed PTCA with acute occlusion, despite measures including larger balloon size, higher pressures, intracoronary nitroglycerine, and sublingual nifedipine. The initial published report involved four patients in whom PTCA was unsuccessful with total or subtotal occlusion with chest pain and ECG evidence for ischemia [16]. After prolonged inflation with the PBC (14–31 minutes), 3 of 4 had reduction of the stenosis and avoided CABG (Table 12-3). The fourth underwent successful CABG.

To investigate the safety of the PBC in humans, 50 consecutive patients undergoing single-vessel PTCA (with side branches in 56%) were examined with serial electrocardiograms and cardiac enzymes to establish evidence

Table 12-3. PBC after failed PTCA

Pt.	Initial obstruction	After PTCA	After PBC	Duration (min)
1	95%	100%	0%	17
2	95%	95%	50%	14
3	95%	100%	95%	18
4	95%	100%	25%	31

PBC = perfusion balloon catheter; PTCA = percutaneous transluminal coronary angioplasty. From Stack RS et al. Perfusion balloon catheter. *Am J Cardiol* 1988; 61:77G–80G. With permission.

for myocardial damage, with plasma hemoglobin, serum haptoglobin, and lactic dehydrogenase for evidence of hemolysis (25 patients), and with ventriculography to assess changes in myocardial function (15 patients) [20]. The inflation time was 15 minutes and antegrade flow was at least TIMI 2 in all patients. There was no ECG evidence of infarction (>1 mm ST elevation or new Q waves) and cardiac enzymes were negative. There was no evidence of intravascular hemolysis with any of the tests performed. The ejection fraction remained unchanged (60% pre versus 61% post). These data showed that prolonged balloon inflation with the PBC in humans can be accomplished without evidence for myocardial damage or hemolysis.

Further human studies were reported in 1988 on patients undergoing routine PTCA [21]. Those with lesions not suitable for the PBC (see below) were excluded. Dilatations were performed three times — first with a conventional Simpson-Roberts catheter at 6 atm until the development of severe chest pain >4 mm ST elevation, widened QRS, hypotension, or arrhythmias (bradycardia <40 bpm, sequential PVCs or ventricular tachycardia). Then the PBC catheter was placed at 6 atm until the above endpoints were reached, or for 10 minutes. A third dilatation was then performed using the standard balloon. Eleven patients were studied, eight men and three women, all with single lesions (RCA 5, LAD 3, CX 3) with mean stenosis 84 ± 10%. All patients had a prolongation in balloon inflation time using the PBC, with 5 of 11 having no ECG changes with balloon inflation for 10 minutes. The mean inflation duration increased from 107 seconds using the standard balloon to 513 seconds using the PBC. The mean ST change and chest-pain scores were lower using the PBC: ST elevation 2.4 ± 1.7 mm in the standard group versus 0.3 ± 0.5 in the PBC group (Table 12-4). Injection during PBC inflation

Table 12-4. Electrocardiographic and clinical data during standard and autoperfusion angioplasty

	ST elevation (mm)	Chest pain	Mean aortic pressure (mmHg)
SR1	2.4 ± 1.7	6.1 ± 2.1	90 ± 10
	$p = 0.002^1$	$p = 0.003^1$	NS
PBC	0.3 ± 0.5	3.2 ± 3.5	91 ± 18
	$p = 0.002^2$	$p = 0.07^2$	NS
SR2	1.9 ± 1.3	5.2 ± 3.1	95 ± 14

Values are mean ± SD.
ST evaluation = maximum ST elevation in any lead; SR1 = standard dilatation before PBC; PBC = perfusion balloon catheter; SR2 = standard dilation after PBC; NS = not significant.
[1] PBC versus SR1; [2] PBC versus SR2.
From Quigley PJ et al. Myocardial protection during coronary angioplasty with an autoperfusion balloon catheter in humans. *Circulation* 1988; 78:1128–1134. With permission of the American Heart Association, Inc.

showed TIMI 3 flow in seven patients and TIMI 2 flow in three, with inability to opacify the distal vessel in one. Five patients had to terminate PBC inflation before 10 minutes, because of angina in three, PVCs in one, and for no stated reason in one.

Similar results were reported by Turi et al. in 1988 using the U.S.C.I. autoperfusion balloon catheter [22]. Following an initial 1 minute inflation with a standard balloon, 18 patients were randomized to a second inflation with a standard balloon for 1 minute or with the autoperfusion balloon for 2 minutes. In the standard group, ST elevation was 0.35 ± 0.04 mV compared with 0.37 ± 0.04 for the initial inflation. However, in the autoperfusion group the ST elevation was only 0.16 ± 0.09 mV compared with 0.48 ± 0.1 for the initial inflation.

CURRENT USE

The current model of the Stack PBC has a balloon made of modified polyethylene (PE600™) and has a microglide™ coating [23]. It has 10 proximal side holes and four distal side holes with a radioopaque marker at the distal end and in the middle of a 20-mm balloon. Its specifications are shown in Table 12-5.

Our current technique for using the catheter is as follows. All patients are premedicated with aspirin 325 mg qd and persantine 100 mg t.i.d. before the procedure. Angioplasty is performed via the femoral approach using an 8 Fr arterial sheath and guiding catheter. Twelve thousand units of heparin are given at the beginning of the procedure and further intravenous heparin is given as needed to maintain the activated clotting time at >300 seconds. After arteriography of the target lesion in two orthogonal views the autoperfusion catheter with a balloon to artery ratio of 1:1.1 is prepared and advanced across the lesion over a 0.018-in. hi-torque floppy guidewire. The guide catheter is then withdrawn slightly from the coronary ostium (0.5–1 cm) to facilitate entry of blood into the proximal side holes. The balloon is inflated gradually to 6 atm over 3 minutes. Once the balloon is inflated, the guidewire is pulled back and additional haparin is given down the central lumen at a rate of 1000 U every 3 minutes. The rate of flow at the end of the dilatation is documented by reinserting the guide catheter and injecting contrast proximally while the

Table 12-5. Specifications of the Stack PBC

Balloon size (mm)	Shaft diameter (French)	Profile (in.)
2.5	4.5	0.059
3.0	4.5	0.060
3.5	4.5	0.062

balloon remains inflated. After dilatation is completed, the guidewire is reinserted, taking care not to pass the wire out the side holes, and the balloon is deflated. The balloon is then withdrawn into the aorta, and arteriography is repeated. If initial inflation is unsuccessful (persistant stenosis, thrombosis, filling defect, large dissection, etc.), the balloon is passed across the lesion again and further dilatations at higher inflation pressures (max. 8 atm), for longer duration, or with a larger balloon are performed. Following successful inflation, the patient is returned to the ward, heparin is continued overnight, and sheaths are removed the next morning. If successful PTCA cannot be performed due to persistant acute occlusion, the PBC catheter is left in place across the lesion while preparations are made for emergency CABG.

Due to the design of the catheter, not all lesions are suitable for PTCA using the PBC. There is the possibility of damage to the vessel from the portion of the device extending beyond the balloon, and therefore angulated or tandem lesions are not suitable. In lesions close to major side branches, balloon inflation will occlude these vessels and produce ischemia. The profile of the PBC is larger than standard balloons, making it somewhat more difficult to place. Finally, an adequate blood pressure is required to provide the pressure needed for passive perfusion across the balloon. Thus, patients in cardiogenic shock should first be treated with an intraaortic balloon pump prior to insertion of the PBC. Lesion characteristics that may preclude use of the PBC are shown in Table 12-6.

CURRENT ROLE FOR THE PBC

There are four potential roles for the PBC: for routine PTCA, to salvage failed PTCA, to perform PTCA in those patients with lesions otherwise not suitable to PTCA, and to maintain perfusion while preparations are made for emergency CABG in persistently occluded vessels.

Routine PTCA with the PBC

The results of the use of the PBC for routine PTCA at Duke and at Christ Hospital in Ohio in our first 122 patients have been carefully evaluated [24,25].

Table 12-6. Lesion exclusion criteria for PBC

1. Ostial stenosis >50%
2. Target lesion ≥1.5 cm
3. Stenosis ≥50% within 2 cm of target lesion
4. Major side branch within 1 cm of lesion
5. Sharp angulation within 2 cm distal to lesion

The mean age of the patients was 58 years, and there were 86 men and 36 women. A single lesion was attempted using the PBC in all patients. The target lesion was in the RCA in 54, LAD in 61, and Cx in 7. A preliminary dilatation for <60 seconds using a standard balloon catheter (2.0 or 2.5 mm) to allow for easier placement was performed before PBC in 48% (Table 12-7).

PTCA was successful in 98% of patients. In one patient the procedure was complicated by major occlusive dissection requiring emergency CABG, which was successful. A second patient had in-hospital reocclusion, which was also treated with successful CABG (Table 12-8).

Repeat six month coronary arteriography was obtained in 83% of patients, with a restenosis rate of 42% (restenosis defined as >50% stenosis in dilated segment) (Table 12-8).

These preliminary results suggest that prolonged dilatations with the PBC may decrease the rate of acute complications, while the long-term restenosis rate remains similar to our restenosis rate with standard angioplasty.

Use of the PBC for vessel salvage after failed PTCA

A second major use of the PBC at our institution is in cases of failed standard PTCA, which results in total or subtotal occlusion, which normally would require emergency CABG. In a group of 28 patients, prolonged inflation with the PBC (21.4 ± 9.3 minutes) was performed [26]. Success, defined as a

Table 12-7. Patient characteristics for use of PBC for routine PTCA

Sex	
male	86
female	36
Lesion site	
RCA	54
LAD	61
CX	7

Table 12-8. Results for use of PBC for routine PTCA

Successful PTCA	120
Dissection and emergency CABG	1
In-hospital reocclusion and CABG	1
Restenosis	42%

residual stenosis of ≤50%, was achieved in 16 of 28 (57%). There were no deaths. Of the unsuccessful patients, 10 underwent CABG. In the successful group only one had a small increase in CK-MB and two had in-hospital restenosis or reocclusion and underwent CABG (Table 12-9). In conclusion, the PBC was able to salvage vessel patency in 50% of patients with initially failed PTCA who otherwise would have required emergency CABG.

Leitschuh et al. at Boston University have reported similar results in patients with coronary dissections during PTCA [27]. In 48 patients treated with standard balloon catheters, the need for emergency CABG was 23% and the major complication rate (death, emergency CABG, or myocardial infarction) was 48%. By using the PBC in their next 22 patients, these rates were reduced to 5% and 18%, respectively.

Use of PBC to allow PTCA in patients with otherwise unsuitable lesions

Hodes et al. at Indiana Heart Institute reported on 17 patients with dissections resulting in occlusion during PTCA, as well as four patients who could not tolerate standard PTCA because of the development of severe ischemia (left main lesion in one, ostial RCA in two, and LAD in one) [28]. Use of the Stack PBC resulted in successful PTCA in 15 of the 21 patients. Besides confirming the above studies showing the use of the PBC as salvage for failed PTCA, these results illustrate a third potential use of the PBC, that is, to allow PTCA in patients who otherwise cannot tolerate standard PTCA due to high risk anatomy.

Use of PBC as bridge to CABG

A fourth use of the PBC is to allow myocardial perfusion in patients with failed PTCA while preparations are made for emergency surgery. We have previously shown that the use of a simple reperfusion catheter allows safer surgery. Although no published results are available on the results of CABG after using the PBC, the current practice in our laboratory is to transfer

Table 12-9. Use of PBC after failed standard PTCA

Number of patients: 28
Balloon inflation time: 21.4 ± 9.3 minutes.
Success (≤50% residual stenosis): 16 (57%)
Deaths: 0

patients after failed PTCA to the operating room with the PBC in place. The animal studies discussed above suggest that myocardial protection, at least in dogs, is provided for occlusions of as long as 90 minutes to 6 hours. A unique use of the PBC has been in cases of coronary artery perforation during interventional procedures in which the PBC is inflated ascross the area of perforation, thus sealing off the leak in the vessel wall, while at the same time providing perfusion while arrangements are made for emergency surgery.

FUTURE DIRECTIONS

New models of the PBC are under development to resolve some of its limitations for use in certain lesions as discussed above. For example, catheters with lower profiles are under development.

Currently a large multicenter prospective randomized clinical study is underway to test the hypothesis that primary PTCA with prolonged inflations will provide better in-hospital anatomic and clinical success and reduce long-term restenosis. Patients not having an acute MI and with lesions that are suitable for the PBC are randomized to short versus long inflations. The short arm consists of two 60-second inflations at a maximum of 6 atm. Prolonged inflations are performed by gradually inflating at 1 atm every 30 seconds to 6 atm and leaving the balloon up for 15 minutes. PTCA is considered successful if the residual lesion is $\leq 50\%$. If the initial result is unsatisfactory, further dilatations are performed with larger balloons, for longer time periods, or at higher pressures. Outcomes measured include ischemia, myocardial infarction, restenosis, death, repeat PTCA, and CABG. Patients are followed for 6 months with clinical follow-up, exercise treadmill test, and relook cardiac catheterization. It is anticipated that the study will be concluded by the end of 1991.

In summary, as documented by the animal and human studies discussed in this chapter, the use of autoperfusion catheters permits the safe performance of PTCA with prolonged inflation time. Data currently available suggest that the ability to allow perfusion during PTCA can effectively salvage many cases of failed PTCA as well as provide a bridge to safer emergency surgery. High risk lesions may also be approached more safely with the use of autoperfusion catheters. Whether prolonged inflation will improve the results of routine PTCA is still to be determined.

REFERENCES

1. Kaltenbach M, Kober G. Can prolonged application of pressure improve the results of coronary angioplasty (TCA)? *Circulation* 1982; 66(Suppl. II):123.
2. Kaltenbach M, Beyer J, Walter S, Klepzig H, Schmidts L. Prolonged application of pressure in transluminal coronary angioplasty. *Cathet Cardiovasc Diag* 1984; 10:213–219.

3. Palazzo A, Gustafson GM, Santilli E, Kemp HG Jr. Unusually long inflation times during percutaneous transluminal coronary angioplasty. *Cathet Cardiovasc Diag* 1988; 14:154–158.
4. Lasala JM, Cleman MW. Myocardial protection during percutaneous transluminal coronary angioplasty. *Cardiol Clin* 1988; 6(3):329–343.
5. Zalewski A, Goldberg S. Protection of the ischemic myocardium during coronary angioplasty. *Cardiovasc Clin* 1988; 19:79–98.
6. Erbel R, Clas W, Busch U, von Seelen W, Brennecke R, Blomer H, Meyer J. New balloon catheter for prolonged percutaneous transluminal coronary angioplasty and bypass flow in occluded vessels. *Cathet Cardiovasc Diag* 1986; 12:116–123.
7. Turi Z, Campbell CA, Kloner RA. The autoperfusion balloon angioplasty catheter prevents ischemia during prolonged balloon inflation. *JACC* 1987; 9:106A.
8. Turi ZG, Campbell CA, Gottimukkala MV, Kloner RA. Preservation of distal coronary perfusion during prolonged balloon inflation with an autoperfusion angioplasty catheter. *Circulation* 1987; 75(6):1273–1280.
9. Turi ZG, Rezkalla S, Campbell CA, Kloner RA. Left main coronary angioplasty: Preservation of distal blood flow using a new "autoperfusion" balloon catheter. *Circulation* 1987; 76(Suppl. IV):466.
10. Stack RS, Califf RM, Phillips HR, Pryor DB, Quigley PJ, Bauman RP, Tcheng JE, Greenfield JC Jr. Interventional cardiac catheterization at Duke Medical Center. *Am J Cardiol* 1988; 62:3F–24F.
11. Hinohara T, Simpson JB, Phillips HR, Behar VS, Peter RH, Kong Y, Carlson EB, Stack RS. Transluminal catheter reperfusion: A new technique to reestablish blood flow after coronary occlusion during percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1986; 57: 684–686.
12. Hinohara T, Simpson JB, Phillips HR, Stack RS. Transluminal intracoronary reperfusion catheter: A device to maintain coronary perfusion between failed coronary angioplasty and emergency coronary bypass surgery. *JACC* 1988; 11:977–982.
13. Ferguson TB, Hinohara T, Simpson J, Stack R, Wechsler AS. Catheter reperfusion to allow optimal coronary bypass grafting following failed transluminal coronary angioplasty. *Ann Thorac Surg* 1986; 42:399–405.
14. Sundram P, Harvey JR, Johnson RG, Schwartz MJ, Baim DS. Benefit of the perfusion catheter for emergency coronary artery grafting after failed percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1989; 63:282–285.
15. Collins GJ, Ramirez NM, Hinohara T, Klopovic Z, Phillips HR, Stack RS. The perfusion balloon catheter: A new method for safe prolonged coronary dilation. *JACC* 1987; 9:106A.
16. Stack RS, Quigley PJ, Collins G, Phillips HR. Perfusion balloon catheter. *Am J Cardiol* 1988; 61:77G–80G.
17. Campbell CA, Rezkalla S, Kloner RA, Turi ZG. The autoperfusion balloon angioplasty catheter limits myocardial ischemia and necrosis during prolonged balloon inflation. *JACC* 1989; 14:1045–1050.
18. Zalewski A, Berry C, Kosman ZK, Shi Y, Goldberg S. Myocardial protection with autoperfusion during prolonged coronary artery occlusion. *Am Heart J* 1990; 119:41–46.
19. Christensen CW, Lassar TA, Daley LC, Rieder MA, Schmidt DH. Regional myocardial blood flow with a reperfusion catheter and an autoperfusion balloon catheter during total coronary occlusion. *Am Heart J* 1990; 119:242–248.
20. Muhlestein JB, Quigley PJ, Phillips HR, Smith JE, Enos SM, Navetta FI, Tcheng JE, Stack RS. Does myocardial damage or hemolysis occur during prolonged perfusion balloon angioplasty? *JACC* 1990; 15:250A.
21. Quigley PJ, Hinohara T, Phillips HR, Peter RH, Behar VS, Kong Y, Simonton CA, Perez JA, Stack RS. Myocardial protection during coronary angioplasty with an autoperfusion balloon catheter in humans. *Circulation* 1988; 78:1128–1134.
22. Turi ZG, Rezkalla S, Campbell CA, Kloner RA. Amelioration of ischemia during angioplasty of the left anterior descending coronary artery with an autoperfusion catheter. *Am J Cardiol* 1988; 62:513–517.
23. Data provided by Advanced Cardiovascular Systems, Mountain View, CA.
24. Quigley PJ, Kereiakes DJ, Abbottsmith CW, Bauman RP, Tcheng JE, Muhlestein JB, Phillips HR, Stack RS. Prolonged autoperfusion angioplasty: Immediate clinical outcome and angiographic follow-up. *JACC* 1989; 13:155A.

25. Quigley P. Early and late outcome following prolonged autoperfusion angioplasty. Unpublished.
26. Smith JE, Quigley PJ, Tcheng JE, Bauman RP, Thomas J, Stack RS. Can prolonged perfusion balloon inflations salvage vessel patency after failed angioplasty? *Circulation* 1989; 80: II-373.
27. Leitschuh ML, LaRosa D, Currier JW, Mills RM, Jacobs AK, Ruocco NA Jr., Faxon DP. The "Stack Perfusion Catheter" improves outcome following dissection during coronary angioplasty. *JACC* 1990; 15:250A.
28. Hodes ZI, Rothbaum DA, Linnemeier TJ, Landin RJ, Ball MW, Giebel RA. Use of the ACS Stack Perfusion Dilatation catheter in PTCA to avoid coronary artery bypass surgery. *JACC* 1989; 13:155A.

13. SYNCHRONIZED CORONARY VENOUS RETROPERFUSION DURING CORONARY ANGIOPLASTY

SHEILA KAR, ALICE K. JACOBS, AND DAVID P. FAXON

INTRODUCTION

Synchronized diastolic coronary venous retroperfusion is a technique by which autologous arterial blood is shunted from the femoral artery into the coronary veins. Phasic diastolic occlusion of the coronary sinus by a balloon catheter compartmentalizes the coronary venous system, preventing regurgitation of arterial blood into the right atrium. Triggered collapse of the balloon during systole facilitates normal physiologic coronary venous drainage and prevents the complications of prolonged elevation of coronary sinus pressure [1,2].

HISTORIC BACKGROUND

The concept of maintaining myocardial viability by perfusing arterial blood via the coronary veins was first conceived by Pratt in 1893 [3], who demonstrated that cardiac contractions in an extirpated feline heart could be maintained for hours when the right heart was perfused. This was followed by Gross et al. [4], Gregg et al. [5,6], and Beck et al. [7,8], who demonstrated that ligation of the coronary sinus enhanced survival in experimental models subjected to ischemia. In fact, Beck [9] worked on 200 patients, in whom he surgically anastomosed the coronary sinus to the aorta via a vein graft. Although relief of ischemia was obtained, there were complications, such as myocardial hemorrhage and edema due to increased coronary venous press-

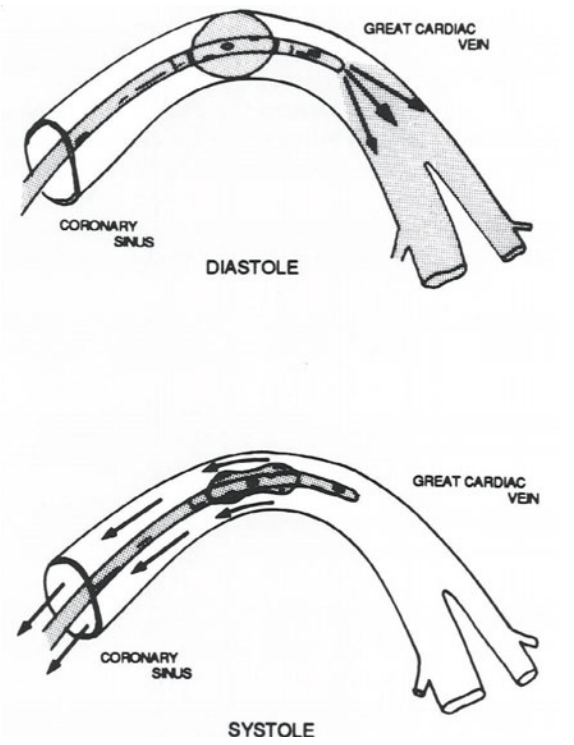

Figure 13-1. Schematic representation of the phasic pulsation of the balloon of the retroperfusion catheter. During ventricular diastole, the balloon inflates and blood is propelled retrograde towards the ischemic zone. During systole, the balloon deflates with cessation of blood flow, permitting coronary venous drainage.

ures. Since then, several investigators have demonstrated myocardial protection by retrograde arterial perfusion during open-heart surgery [10–13].

In 1976, Meerbaum and colleagues [1] first described the diastolic retroperfusion technique. Synchronization allowed time sharing of the cardiac cycle, whereby arterial perfusion along with balloon occlusion of the coronary sinus would occur in diastole, and balloon deflation and cessation of blood flow allowing venous drainage in systole, thus preventing undesirable rise in coronary venous pressures (Figure 13-1).

In 1984, Mohl et al. [14] developed the technique of "Pressure controlled intermittent coronary sinus occlusion" (PICSO), based on the hypothesis that the efficacy obtained by the Beck procedure [7,8] was due to enhanced washout of metabolites. The technique intermittently occluded the coronary sinus,

resulting in maximal venous engorgement and therefore optimal perfusion and washout. The coronary sinus pressure elevated rapidly, often reaching mean systemic pressures and then assumed a plateau, which represented complete filling of the venous capacitance circulation. The balloon was then deflated allowing for maximum redistribution and effective washout of toxic metabolites, but unfortunately, edema could also occur.

This technique was shown to significantly reduce infarct size to 56% of the risk area compared to 99% of the risk area in the untreated group in the canine model [14]. Jacobs et al. [15] studied the effects of PICSO on reperfusion. In canines treated with PICSO during reperfusion, the infarct size was 17% of the area at risk compared to 33% in the reperfusion alone group. Similar efficacy was seen by Guerci et al. [16] in a 3-hour occlusion and 24-hour reperfusion canine model.

THE RETROPERFUSION SYSTEM

The current retroperfusion device (Retroperfusion Systems, Inc., Costa Mesa, CA) consists of an electronic pumping console, a specially designed retroperfusion catheter, and an arterial catheter. Arterial blood is withdrawn from the femoral artery through a 10-in. long 8 Fr arterial catheter, featuring end and side holes at its distal end, which is introduced through an 8 Fr sheath placed percutaneously in the femoral artery. The arterial blood supply catheter is connected to the inlet of the disposable retroperfusion pump cassette, which is housed within the system console, and pumped during diastole by means of a piston whose motion is triggered by the R wave of the monitored ECG. The outlet of the pumping cassette is, in turn, connected to the blood infusion lumen of the retroperfusion catheter (Figure 13-2). The latter is a radiopaque, 8.5 Fr triple lumen catheter, featuring an inflatable balloon located 1 cm from the distal end of the catheter (Figure 13-3). Carbon dioxide gas is delivered via the catheter's second lumen to inflate the balloon during diastole (to 10 mm in diameter at full gas pressure), applying a fixed volume (0.75 cc) of CO_2 from a pressurized cylinder. The third lumen is used to continuously monitor the coronary venous pressure (Figure 13-4). Previous studies have shown that severe damage to venules occurred when coronary venous pressures exceed 60 mmHg peak or 40 mmHg mean pressure [17,18]. The pump is equipped with a safety mechanism that terminates retroperfusion if coronary venous pressures exceed prescribed limits. The maximum flow rates delivered by the current retroperfusion pump system range up to 250 ml/min.

SYNCHRONIZED RETROPERFUSION IN EXPERIMENTAL STRUDIES

Effects of retroperfusion on infarct size, perfusion and metabolism

Numerous studies have validated the synchronized retroperfusion technique [1,17–22]. Preclinical studies by Drury et al. [17] demonstrated safety, by the absence of myocardial edema, hemorrhage, and hemolysis in the canine

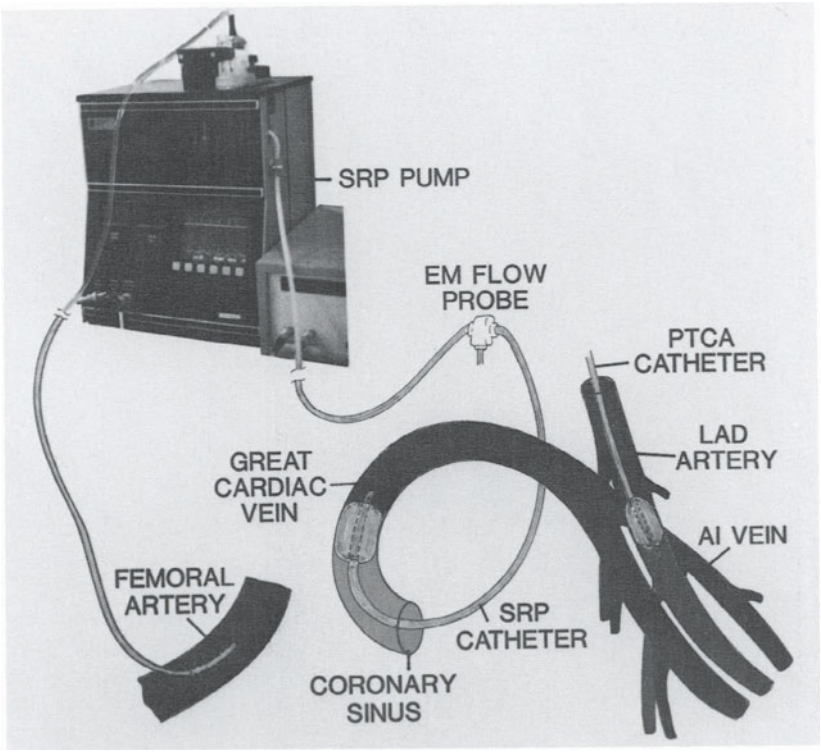

Figure 13-2. Schematic representation of the method by which synchronized coronary venous retroperfusion is accomplished. SRP = synchronized retroperfusion; EM = electromagnetic; PTCA = percutaneous transluminal coronary angioplasty; LAD = left anterior descending coronary; AI = anterior interventricular.

model. Yamazaki et al. [18] showed significant reduction in infarct size with retroperfusion compared to an untreated group (19% versus 56% of area at risk) after 6 hours of LAD occlusion in the canine model. Geary et al. [19] also demonstrated a significant reduction in histological infarct size with retroperfusion in a 4-hour LAD occlusion, 24-hour reperfusion model (58% versus 94%) in baboons.

Berdeaux et al. [22] assessed myocardial blood flow during retroperfusion using radioactive microspheres, and demonstrated an epi-endo flow ratio of 1:1.4, indicating preferential flow to the endocardium. Positron emission tomography was utilized by O'Byrne and colleagues [23] to demonstrate the effects of retroperfusion on myocardial perfusion and glucose metabolism. During retroperfusion, it was observed that there was selective delivery of

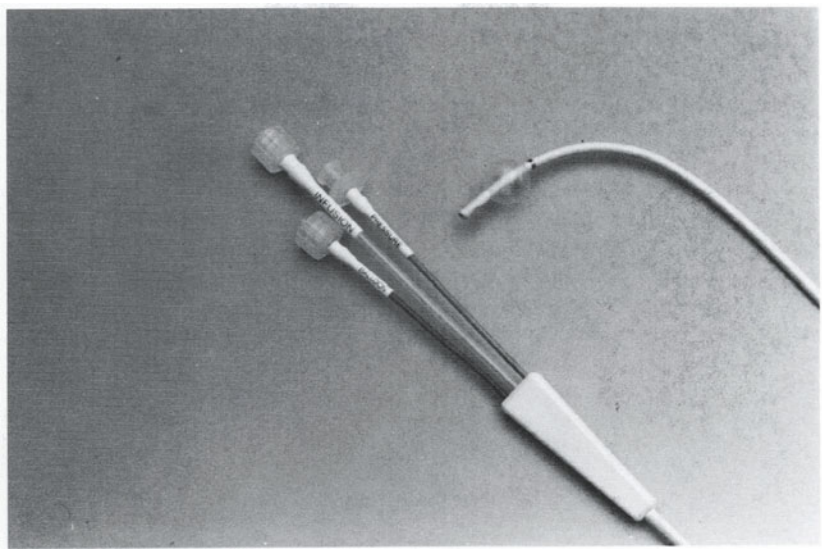

Figure 13-3. Triple-lumen, 8.5 Fr, balloon-tipped, gas-inflatable retroperfusion catheter. From Retroperfusion systems, Inc., Costa Mesa, CA, USA. With permission.

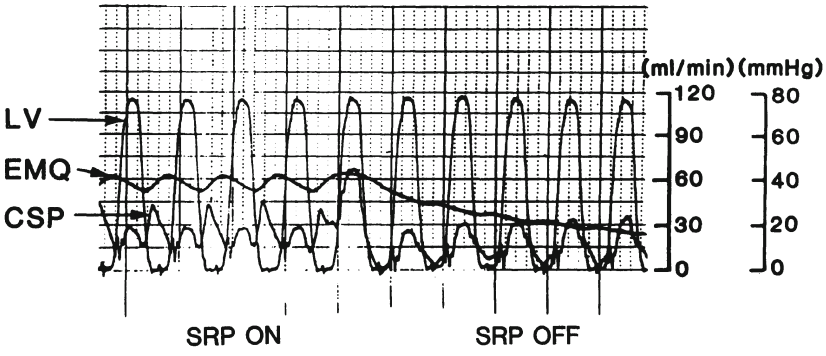

Figure 13-4. Coronary venous pressure tracing showing diastolic augmentation with synchronized retroperfusion. The systolic pressure remains relatively unchanged, indicating that normal systolic venous drainage is permitted. The pressure was measured through the pressure lumen of the retroperfusion catheter. LV = left ventricular pressure; EMQ = electromagnetic flow meter tracing; CSP = coronary venous pressure; SRP = synchronized retroperfusion.

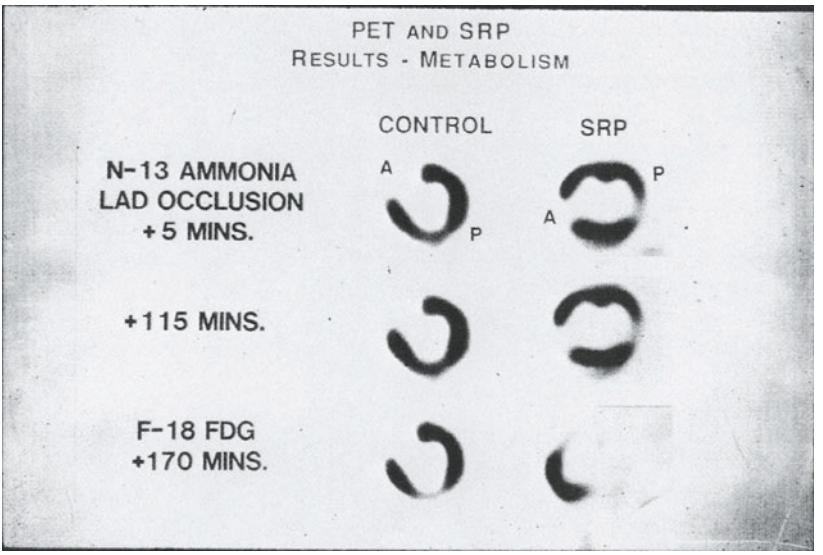

Figure 13-5. Positron emission tomographic short axis images obtained from an untreated dog (control, left panel) and a retroperfusion-treated dog (SRP, right panel), demonstrating the effect of retroperfusion on glucose metabolism. Following LAD occlusion, there are perfusion defects in the anterior wall (A) but normal perfusion in the posterior wall (P) in both the control and retroperfusion-treated dogs, demonstrated by the uptake of the flow tracer N-13 ammonia (upper panel). These perfusion defects remain unchanged at 115 minutes post-LAD occlusion (middle panel). Retroperfusion was then started in the animal on the right. Approximately 3 hours post-occlusion, there was no glucose metabolism in the control animal but preserved metabolism in the retroperfused animal, denoted by uptake of F-18 deoxyglucose (FDG, lower panel). From Heinrich R. Schelbert, M.D., Ph.D., Dept. of Radiological Sciences, UCLA Med. Ctr, Los Angeles, CA, USA. With permission.

the flow tracers to the risk zone and selective uptake of glucose after 2 hours of ischemia, indicating preservation of glucose metabolism in the risk area, whereas in the untreated animal there was absence of uptake (Figure 13-5). These experimental studies demonstrated that the synchronized retroperfusion technique preserves myocardial function, selectively perfuses and maintains viability of the ischemic area, reduces infarct size, and is safe.

Infusion of Pharmacologic Agents via the Coronary Sinus

Delivery of pharmacologic agents via the coronary veins has also been studied. Simon et al. [24] and Otsu et al. [25] found an increased concentration of lidocaine in the ischemic area when given by retroinfusion. Karagueuzian et al. [26] found enhanced antiarrhythmic effects by retroinfusion of procainamide, and Ryden et al. [27] reported significantly higher tissue concen-

trations of metoprolol in the ischemic zones when given via the coronary veins than when given by the conventional intravenous route (2002 versus 238 pmol/g). Tadokoro et al. [28] showed that there was significant reduction in infarct size when diltiazem was given via the coronary veins compared to intravenous administration in a 1-hour LAD occlusion followed by 3-hour reperfusion porcine model. Similar enhanced protection was demonstrated in the canine model by Hatori et al. [29], using oxygen free-radical scavengers, superoxide dismutase, and catalase. The infarct size was 11% and 31% of the risk area, when the scavengers were given via the coronary veins and systemically, respectively. Miyazaki et al. [30] noted significant rapid (14 versus 28 minutes) and effective (lysis success rate 83% versus 50% of clots) thrombolysis when tissue-type plasminogen activator was administered by retroinfusion compared to the intravenous route. Similar results have been reported by retroinfusion of streptokinase [31,32].

SYNCHRONIZED RETROPERFUSION IN CLINICAL STUDIES

Coronary sinus catheterization is a safe technique generally performed for measurement of coronary blood flow, oxygen consumption, and lactate extraction [33–35]. Gensini et al. [36] and more recently, Faxon and colleagues [37], demonstrated that coronary sinus occlusion can also be safely performed in humans. Faxon observed that coronary sinus occlusion pressure during systole was significantly lower than left ventricular pressure and that there was no relation between these pressures. However, throughout diastole, the coronary sinus occlusion pressure was similar to left ventricular pressure and there was a close correlation between the left ventricular end-diastolic pressure and end-diastolic coronary sinus occlusion pressure (Figure 13-6). The similarity in pressures is likely due to the interconnections that exist between veins and the left ventricular chamber. There were no significant complications, or changes in the heart rate or arterial blood pressure, from brief occlusion of the coronary sinus.

Retroperfusion during unstable angina

The first clinical performance of synchronized retroperfusion during unstable angina was reported by Gore et al. [38]. This report included five patients with unstable angina refractory to "maximum" medical therapy and believed to be at extremely high risk for a fatal cardiac event. Retroperfusion was performed using an ECG-synchronized automatic pump, which propelled blood through an autoinflatable balloon catheter during each diastole. The number of anginal episodes were significantly reduced during retroperfusion, as was the requirement of intravenous and sublingual nitroglycerine. In 4 of 5 patients there was normalization of the ischemic ECG changes within 10 minutes of instituting retroperfusion. Barnett et al. [39,40] reported the effects of retroperfusion in eight patients with unstable angina and myocardial infarction, of whom two were in cardiogenic shock. During retroperfusion there was

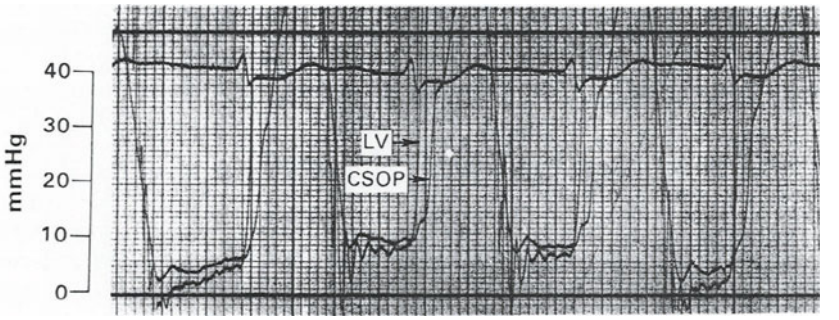

Figure 13-6. Simultaneous recording of coronary sinus occlusion pressure (CSOP) and left ventricular (LV) diastolic pressure in a patient with atrial fibrillation. Throughout diastole, a close relation between LV pressure and CSOP is maintained. From Faxon DP et al. [37]. With permission.

reduction in the ST-segment elevation, with a concommitant improvement in wall motion of the infarct zone, seen on two-dimensional echocardiography. These studies demonstrate the feasibility and safety of retroperfusion in unstable angina and evolving myocardial infarction and suggest clinical efficacy.

Retroperfusion during coronary angioplasty

Angioplasty is an effective treatment for coronary artery stenoses, but it results in transient interruption of regional blood supply, which may cause myocardial ischemia with consequent hemodynamic, electrophysiologic, metabolic, and functional derangements [41–43]. These ischemic changes are of particular concern in high risk patients with large areas of jeopardized myocardium or significant preexistant left ventricular dysfunction. Further, acute closure of the dilated coronary artery occurs in about 5% of all PTCA procedures [44]. This complication is usually managed by bypass surgery, but may sustain a mortality rate as high as 7% [45,46].

Thus there has been development of both myocardial and systemic support techniques aimed at mitigating these ischemic derangements [47]. The systemic support techniques include percutaneous femoro-femoral cardiopulmonary bypass [48–50], hemopump left ventricular assist device [51,52], and intraaortic balloon pumping [53]. These devices provide systemic circulatory support and reduce myocardial oxygen demand, but the blood supply to the jeopardized myocardium is not enhanced, so myocardial ischemia may persist.

The myocardial support techniques include administration of pharmacologic agents [47], infusion of oxygenated fluorocarbon solutions [54–56], and infusion or passive supply of whole blood via the angioplasty catheter distal to the dilatation balloon [57–61]. Although these techniques may allow extension of the PTCA balloon inflation time, they possess certain limitations. The

requirement by some techniques for larger balloon catheter systems may limit their ability to cross a severely stenotic lesion or pass distally within a tortuous vessel. Perfusion may also be ineffective when there are additional sequential stenoses or when the perfusion catheter obstructs a significant side branch.

Synchronized retroperfusion is a myocardial support technique that perfuses arterial blood retrogradely via the coronary venous system. Since the coronary venous system is free of atherosclerosis, it provides a potential alternative route for the percutaneous delivery of oxygenated blood and therapeutic agents to the myocardium that is deprived of blood by a coronary artery occlusion [1,2]. Its efficacy, therefore, is not influenced by the number, location, or degree of stenoses and tortuosity or branching of the coronary artery.

Weiner et al. [62] first reported synchronized retroperfusion during angioplasty of the left anterior descending coronary artery (LAD) in three patients. Each patient underwent four angioplasty balloon dilatations, two with and two without retroperfusion, thus each patient was his/her own control. A significant delay in onset of angina (100 versus 28 seconds) and time to ST-segment change (137 versus 60 seconds) was noted in the retroperfused compared to the untreated inflations. A similar study using retroperfusion during high risk angioplasty in acute ischemic syndromes was reported by Costantini et al. [63]. During PTCA balloon inflations, the cardiac index and stroke work index were significantly preserved with retroperfusion compared to the untreated inflations.

Berland et al. [64] reported the results of 16 patients undergoing retroperfusion during angioplasty of the LAD. There was successful coronary catheterization in 12 of 16 patients within approximately 2 minutes. Forty-eight PTCA balloon inflations were evaluated, 16 during retroperfusion and 32 were untreated control inflations. Thirty-one percent of the treated inflations resulted in angina, as opposed to 72% of the untreated inflations. The average ST-segment elevation in leads V_1-V_4 was significantly lower with retroperfusion compared to control inflation (10 versus 16 mm). The ejection fraction obtained from two-dimensional echocardiography was preserved with retroperfusion. These studies demonstrated that retroperfusion was safe, could be rapidly implemented, reduced ischemia, and preserved both regional and global myocardial function during angioplasty.

RETROPERFUSION DURING ANGIOPLASTY: MULTICENTER TRIAL

A multicenter, randomized controlled study, evaluating feasibility, safety, and efficacy of retroperfusion during coronary angioplasty has been underway since May 1987. Thus far, the study has included 164 patients undergoing angioplasty of the LAD having $\geq$70% diameter stenosis [65].

The 50-cm long retroperfusion catheter was inserted through a 9 Fr internal jugular venous sheath into the right atrium under fluoroscopic control. An attempt was made in each case to place the catheter deep into the coronary sinus, preferably into the great cardiac vein. Retrograde opacification of the

coronary veins following hand injection of contrast material through the infusion lumen (with the retroperfusion catheter balloon inflated and obstructing reverse shunting back into the right atrium) helped confirm both adequate catheter positioning and proper occlusion of the coronary vein by the balloon (Figure 13-7). This ensured unidirectional diastolic propulsion of arterial blood into the ischemic myocardium.

Study protocol

PTCA was performed in the standard manner. Synchronized coronary venous retroperfusion was performed during alternate PTCA balloon inflations, the order of which was randomized. The untreated inflations served as controls.

Hemodynamics (heart rate, aortic blood pressure, and coronary venous pressure) and a single precordial ECG lead (V_3–V_6) were monitored and continuously recorded. The time of onset of angina was determined during all untreated and retroperfused inflations. The severity of the pain was assessed on a semiquantitative scale of 0–4, 0 signifying absence of pain and 4 representing severe pain. ST-segment change was measured 0.06 seconds after the J point and expressed in millimeters as an absolute change from the baseline measurement.

Two-dimensional echocardiograms were recorded in the patients before and during each balloon inflation in apical four-chamber views. A modified centerline method, as described by Jaffe et al. [53], was used to quantify the extent and severity of regional left ventricular wall motion from digitized echo images. Global left ventricular ejection fraction was also calculated.

Results

Data was pooled from multiple centers on 164 patients undergoing LAD angioplasty during retroperfusion. In the 104 patients in whom retroperfusion was established, a total of 499 (LAD) PTCA inflations were reported, 198 with retroperfusion and 301 were untreated. The data are presented by inflations, although per patient analysis gave similar results. Angina occured in 43% of the treated inflations compared to 58% of the untreated inflations ($p < \pm 0.01$), and the severity of the pain was significantly lower with retroperfusion. The average time to the onset of angina was 48 seconds and 38 seconds in the treated and control group, respectively ($p < 0.01$).

Ischemic ST-segment change (>1.0 mV) was noted in 67% of the treated inflations compared to 76% of the untreated inflations (p = NS). The average

Figure 13-7. Venograms of two patients during LAD angioplasty showing (A) proximal filling of all the tributaries of the coronary veins and regurgitation past the nonocclusive balloon (arrow), and (B) distal penetration of the retroperfusate due to adequate SRP balloon catheter position. The venograms were obtained by injecting contrast material into the retroperfusion pump system (LAO views). PTCA = angioplasty balloon; W = PTCA guidewire; AIV = anterior interventricular vein; PV = posterior vein of the left ventricle; MCV = middle cardiac vein; GCV = great cardiac vein; SRP cath = retroperfusion catheter; B = retroperfusion catheter balloon.

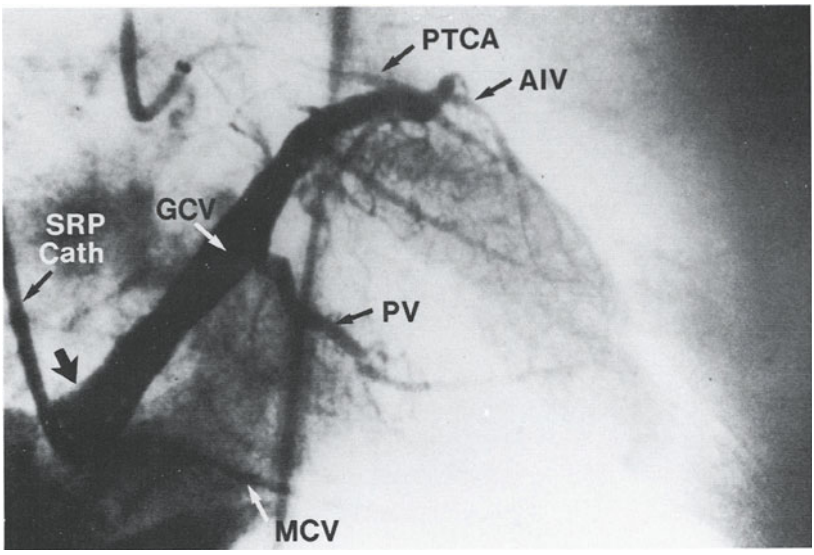

Figure 13-7A

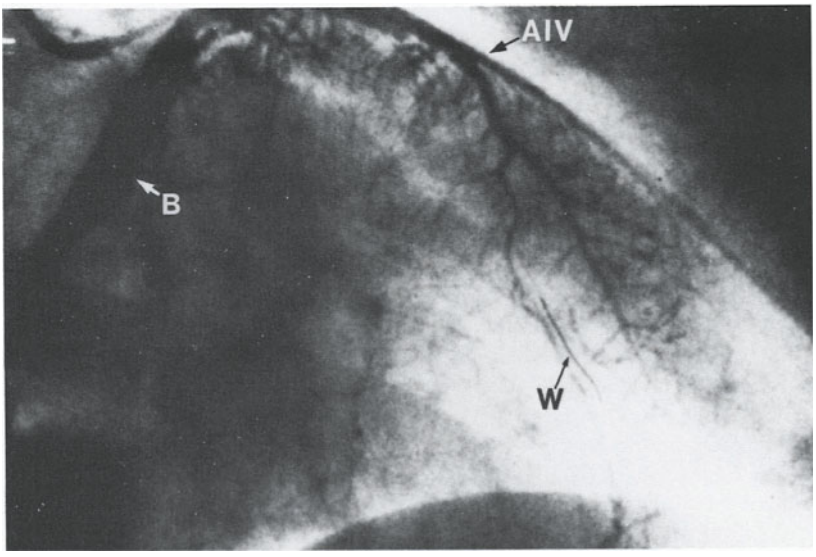

Figure 13-7B

ST-segment change was 2.4 and 3.3 mV in the retroperfused and control groups, respectively ($p < 0.01$).

Blood pressure and heart rate were unchanged during both the retroperfused and untreated inflations. However, the mean coronary venous pressures rose from 8 to 16 mmHg, and maximum coronary venous pressure changed from 14 to 31 mmHg with retroperfusion.

Twenty patients (20%) had echocardiographic images that were quantifiable by the centerline method used in the analysis. The supine position of the patients during angioplasty made it difficult to obtain good-quality echo images. Regional wall motion analysis showed mild hypokinesis in the treated group and dyskinesis in the control group (percent chord shortening 0.5 treated versus −0.5 control group, $p < 0.001$). Moreover, the extent of the left ventricle showing the wall motion abnormality was significantly less with retroperfusion compared to control (21% versus 34%). The global ejection fraction was 44% with retroperfusion and 36% in the control groups ($p < 0.01$).

There was no evidence of hemolysis or any other major adverse effects attributable to retroperfusion in any of the patients.

The advantages of prolonged retroperfusion was observed in five patients, who developed abrupt occlusions of the proximal LAD during angioplasty. These patients were pumped for an average of 4 hours until definitive revascularization therapy, repeat PTCA in one patient, and emergency bypass in the remaining four patients was performed. The coronary sinus was visualized during surgery and was found to be normal. All patients did well postoperatively. These cases indicate that prolonged retroperfusion is safe and may be a valuable myocardial support technique in high risk angioplasty, especially in the event of an abrupt coronary occlusion during angioplasty. It has been reported that the incidence of Q-wave myocardial infarction may be as high as 55–77% and the mortality rate as high as 5–12% after bypass surgery in cases of failed angioplasty [66–68].

The preliminary results documenting the ability of synchronized retroperfusion to ameliorate or retard the onset of ischemia looks promising, but must be interpreted with caution. It is important to note that retroperfusion is not effective in all patients and that, in the majority of patients, the ischemic response is delayed or decreased but not totally prevented or abolished. The efficacy of retroperfusion appears to depend on multiple factors, including retroperfusion flow rates, coronary venous anatomy, retroperfusion catheter, and balloon position in the coronary vein relative to the site of coronary artery obstruction and developed coronary venous pressure in relation to distal coronary artery pressure [2,69]. Therefore, optimization of the technique manipulating these factors, especially coronary sinus pressure and flow, is of critical importance.

The only vessel studied was the LAD; study of retroperfusion in left circumflex and right coronary angioplasty is warranted. The efficacy in these

regions may be less than the LAD, as venous drainage or catheter position may decrease retroperfusion flow. However, the profuse intervenous communications may provide adequate venous access to these areas as well.

Current technical limitations include the need for a 9 Fr sheath in the internal jugular or upper extremity vein. Improvements in catheter design should permit coronary sinus entry from the femoral route.

CONCLUSIONS

Synchronized coronary venous retroperfusion is a safe and feasible technique for the reduction of ischemia during angioplasty. It significantly preserves regional and global myocardial function and appears especially beneficial during an abrupt coronary artery occlusion, thus acting as an effective bridge to definitive therapy. It also shows promise as a mode of therapy for evolving myocardial infarction and medically refractory unstable angina. Clinical studies in these areas are now in progress.

REFERENCES

1. Meerbaum S, Lang TW, Osher JV, Hashimoto K, Lewis GW, Feldstein C, Corday E. Diastolic retroperfusion of acutely ischemic myocardium. *Am J Cardiol* 1976; 37:558–598.
2. Jacobs AK, Faxon DP. Retroperfusion and PTCA. In Topol Ed, *Interventional Cardiology*, W.B. Saunders, Philadelphia, 1990, pp. 477–495.
3. Pratt FH. The nutrition of the heart through the vessels of Thebesius and the coronary veins. *Am J Physiol* 1893; 1:86–103.
4. Gross L, Blum L, Silverman G. Experimental attempts to increase blood supply to the dog's heart by means of coronary sinus occlusion. *J Exp* 1937; 65:91.
5. Gregg DE, DeWald D. Immediate effects of coronary sinus ligation on dynamics of coronary circulation. *Proc Soc Exp Biol Med* 1938; 39:444–456.
6. Gregg DE, Shipley RE. Studies of venous drainage of the heart. *Am J Physiol* 1947; 151:13.
7. Beck CS, Stanton E, Batiuchok W, Leiter E. Revascularization of heart by graft of systemic artery into coronary sinus. *JAMA* 1948; 137:436–442.
8. Beck CS, Leighninger DC. Scientific basis for the surgical treatment of coronary artery disease. *JAMA* 1954; 159:1264.
9. Beck DS. Revascularization of the heart. *Ann Surg* 1948; 128:854.
10. Lillehei CW, Dewald RA, Gott VL, Varco RL. The direct vision correction of calcific aortic stenosis by means of a pump-oxygenator and retrograde coronary sinus perfusion. *Dis Chest* 1956; 30:123.
11. Menasche P, Kural S, Fauchet M, Lavergne A, Commin P, Bercot M, Touicot B, Georgiopoulos G, Piwnica A. Retrograde coronary sinus perfusion: A safe alternative for ensuring cardioplegic delivery in aortic valve surgery. *Ann Thorac Surg* 1982; 34:647.
12. Takahashi M. Retrograde coronary sinus perfusion for myocardial protection in aortic valve surgery. *Nippon Kyobu Geke Gekkai Sesshi* 1982; 30:24–318.
13. Gundry SR, Kirsh MM. A comparison of retrograde cardioplegia versus antegrade cardioplegia in the presence of coronary artery obstruction. *Ann Thorac Surg* 1984; 38:124–127.
14. Mohl W, Glogar DH, Mayr H, Losert U, Socher H, Pachinger O, Wolner E. Reduction of infarct size by pressure-controlled intermittent coronary sinus occlusion. *Am J Cardiol* 1984; 53:923–928.
15. Jacobs AK. The effect of pressure-controlled intermittent coronary sinus occlusion during reperfusion. In Mohl W, Faxon DP, Wolner E, eds. *Clinics of CSI. Proceedings of the Second International Symposium on Myocardial Protection via the Coronary Sinus.* Steinkopff Verlag, Darmstadt, 1986, pp. 345–348.
16. Guerci AD, Ciuffo AA, DiPaula AF, Weisfeldt ML. Intermittent coronary sinus occlusion in dogs: Reduction of infarct size 10 days after reperfusion. *J Am Coll Cardiol* 1987; 9:1075–1081.

17. Drury JK, Yamazaki S, Fishbein M, Meerbaum S, Corday E. Synchronized diastolic coronary venous retroperfusion: Results of a pre-clinical safety and efficacy data. *J Am Coll Cardiol* 1985; 6:328–335.
18. Yamazaki S, Drury JK, Meerbaum S, Corday E. Synchronized coronary venous retroperfusion: Prompt improvement of left ventricular function in experimental myocardial ischemia. *J Am Coll Cardiol* 1985; 5:655–663.
19. Geary GG, Smith GT, Suchiro GT, Seman C, Sire B, McNamara JJ. Quantitative assessment of infarct size reduction by coronary venous retroperfusion in baboons. *Am J Cardiol* 1981; 48:1064–1070.
20. Zalewski A, Goldberg S, Slysh S, Maroko PR. Myocardial protection via coronary sinus interventions: Superior effects of arterialization compared with intermittent occlusion. *Circulation* 1985; 71(6):1215–1223.
21. Chang B-L, Drury JK, Meerbaum S, Fishbein MC, Whiting JS, corday E. Myocardial washout and retrograde blood delivery with synchronized retroperfusion during acute myocardial ischemia. *J Am Coll Cardiol* 1987; 9:1091–1099.
22. Berdeaux A, Farcot JC, Bourdarias JP, Barry M, Bardet J, Giudicelli JF. Effects of diastolic synchronized retroperfusion on regional blood flow in experimental myocardial ischemia. *Am J Cardiol* 1981; 47:1033–1040.
23. O'Byrne G, Nienaber CA, Miyazaki A, Kar S, Araujo L, Drury JK, Corday E, Schelbert HR. Coronary venous retroperfusion: Effect on flow and metabolism in acutely ischemic canine myocardium studied with positron emission tomography (abstr). *J Am Coll Cardiol* 1988; 11(2):86.
24. Simon P, Jacobs AK, Faxon DP, Minihan AC, Coats WD, Ryan TJ. Lidocaine delivery via the coronary sinus results in high concentrations in ischemic myocardium (abstr). *J Am Coll Cardiol* 1988(II):87.
25. Otsu F, Carew TE, Maroko PR. Myocardial concentration and antiarrhythmic effect of lidocaine via the coronary veins (abstr). *J Am Coll Cardiol* 1985; 5:467.
26. Karageuezian HS, Ohta M, Drury JK, Fishbein MC, Meerbaum S, Corday E, Mandel WJ, Peter T. Coronary venous retroperfusion of procainamide: A new approach for the management of spontaneous and inducible sustained ventricular tachycardia during myocardial infarction. *J Am Coll Cardiol* 1986; 7:551–563.
27. Ryden L, Tadokoro H, Sjoquist P-O, Kar S, Ervik M, Corday E. Pronounced accumulation of metoprolol in ischemic myocardium after coronary venous retroinfusion. *J Cardiovasc Pharmacol* 1990; 15(1):22–28.
28. Tadokoro H, Miyazaki A, Satomura K, Kaul S, Fishbein MC, Corday E. Profound infarct size reduction with coronary venous retroinfusion of diltizaem in pigs (abstr). *J Am Coll Cardiol* 1988; 11:65.
29. Hatori N, Miyazaki A, Tadokoro H, Ryden L, Moll J, Rajagopalan RE, Fishbein MC, Meerbaum S, Corday E, Drury JK. Beneficial effects of coronary venous retroinfusion of superoxide dismutase and catalase on reperfusion arrhythmias, myocardial function, and infarct size in dogs. *J Cardiovasc Pharmacol* 1989; 14:396–404.
30. Miyazaki A, Tadokoro H, Kar S, Corday E, Drury JK. More rapid thrombolysis and infarct size reduction with coronary venous retroinfusion of tissue-type plasminogen activator in dogs (abstr). *Circulation* 1989; 80(4):II-644.
31. Miyazaki A, Drury JK, Hatori N, Corday E. Improved clot lysis and infarct size reduction with coronary venous compared with intravenous infusion of streptokinase (abstr). *J Am Coll Cardiol* 1987; 9(2):82.
32. Meerbaum S, Lang TW, Povzhitkov M, Haendchen RV, Uchiyama T, Broffman J, Corday E. Retrograde lysis of coronary artery thrombus by coronary venous streptokinase administration. *J Am Coll Cardiol* 1983; 1:1262–1267.
33. Ganz W, Tamuruk K, Marcus HJ, Donoso R, Yashida S, Swan HJC. Measurement of coronary sinus blood flow by continuous thermodilution in man. *Circulation* 1971; 44:181–194.
34. Bing RT, Hammond MN, Handelsman C, Powers SR, Spenser FC, Eckenhoff JE, Goodale WT, Hofkenschiel JN, Kety SS. Measurement of coronary blood flow, oxygen consumption and efficiency of the left ventricle in man. *Am Heart J* 1949; 38:1–24.
35. Baim DS, Rothman MT, Harrelson DC. Improved catheter for regional coronary sinus flow and metabolic studies. *Am J Cardiol* 1980; 46:997–1000.
36. Gensini GG, DiGiorgi S, Murad-Netto S. Coronary venous occluded pressure. *Arch Surg* 1963; 86:72–80.

37. Faxon DP, Jacobs AK, Kellet MA, McSweeney SM, Coats WD, Ryan TJ. Coronary sinus occlusion pressure and its relation to intracardiac pressure. *Am J Cardiol* 1985; 56:457–460.
38. Gore JM, Weiner BH, Benotti JR, Sloan KM, Okike ON, 'Cuenoud HF, Gaca JMJ, Alpert JS, Dalen JE. Preliminary experience with synchronized coronary sinus retroperfusion in humans. *Circulation* 1986; 74:381–388.
39. Barnett CR, Touchon CT. Use of coronary venous retroperfusion in acute myocardial ischemia. *Cardiovasc Rev & Rep* 1990; 10:64–65.
40. Barnett CR, Warren SG, Namay DN, Vaughan AN, Touchon RC. Coronary sinus retroperfusion in unstable angina and myocardial infarction (abstr). *Proc Adv Med Instr* 1990; 12.
41. Serruys PW, Wigins W, vanden Brand M, Jeij S, Slager C, Schuerbius JCH, Hugenholtz PG, Brower RW. Left ventricular performance, regional blood flow, wall motion, and lactate metabolism during transluminal angioplasty. *Circulation* 1984; 70:25–36.
42. Hauser AM, Gangadharan V, Ramos RG, Gordon S, Timmis GC. Sequence of mechanical, electrocardiographic and clinical effects of repeat coronary artery occlusion in human beings: Echocardiographic observations during coronary angioplasty. *J Am Coll Cardiol* 1985; 5: 193–197.
43. Wohlgelernter D, Cleman M, Highman HA, Fetterman RC, Duncan JS, Zaret Bl, Jaffe CC. Regional myocardiol dysfunction during coronary angioplasty: Evaluation by two-dimensional echcardiography and 12 lead electrocardiography. *J Am Coll Cardiol* 1986; 7:1245–1254.
44. Cowley MJ, Dorros G, Van Raden M, Detre KM. Acute coronary events associated with percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1984; 53:12c–16c.
45. Detre K, Holubkor R, Kelsey S, et al. Percutaneous transluminal coronary angioplasty in 1985–1986 and 1977–1981: The National Heart, Lung and Blood Registry. *N Engl J Med* 1988; 318:265–270.
46. Dorros G, Cowley MJ, Jandc K, Kelsey SF, Mullins SM, Van Raden M. In-hospital mortality rate in the National Heart, Lung and Blood Institute Percutaneous Transluminal Coronary Angioplasty Registry. *Am J Cardiol* 1984; 53:17c–21c.
47. Lasala JM, Cleman MW. Myocardial protection during percutaneous transluminal coronary angioplasty. *Cardiol Clin* 1988; 6:329–343.
48. Stack RS, Pavlides GS, Juteson G, Schreiber TL, O'Neill. Hemodynamic and metabolism effects of cardiopulmonary support during PTCA (abstr). *J Am Coll Cardiol* 1990; 15(2):250.
49. Vogel RA, Shawl F, Tommasso C, et al. Initial report of the National Registry of Elective Cardiopulmonary Bypass Supported Coronary Angioplasty. *J Am Coll Cardiol* 1990; 15: 23–29.
50. Geamnopoulous C, Peters T, Leya F, Euler D, Wallock M, Onow S, Johnson S, Scanlon P. Does percutaneous cardiopulmonary support protect the heart from ischemic dysfunction during coronary occlusion? (abstr). *J Am Coll Cardiol* 1990; 15(2):42.
51. Smalling RW, Cassidy DB, Merlige M, Felli PR, Wise GM, Barret RL, Wampler RD. Improved hemodynamic and left ventricular unloading during acute ischemia using the hemopump left ventricular assist device compared to intra-aortic balloon counter pulsation (abstr). *J Am Coll Cardiol* 1989; 13(Suppl. A):160.
52. Merhige ME, Smalling RW, Cassidy D, Barett R, Wise G, Short BS, Wampler RK. Effect of hemopump left ventricular assist device on regional myocardial perfusion and function, reduction of ischemia during coronary occlusion. *Circulation* 1989; 80(Suppl. III):III158–III168.
53. Alcan KE, Stertzer SH, Wallsh JE, DePasquale NP, Bruno MS. The rate of intra-aortic balloon counterpulsation in patients undergoing percutaneous transluminal coronary angioplasty. *Am Heart J* 1983; 105:527–530.
54. Jaffe CC, Wohlgelernter D, Cabin HS, Bowman L, Deckelbaum L, Remetz M, Cleman M. Preservation of left ventricular ejection fraction during percutaneous transluminal coronary angioplasty by distal transcathcter coronary perfusion of oxygenated Fluosol DA 20%. *Am Heart J* 1988; 115:1156–1164.
55. Flaherty JT, Jaffin JH, Magovern GJ, Kanter KR, Gardner TJ, Miceli MV, Jacobus WE. Maintenance of aerobic metabolism during global ischemia with perfluorocarbon cardioplegia improves myocardial preservation. *Circulation* 1984; 69:595–592.
56. Cleman M, Jaffe CC, Wohlgelernter D. Prevention of ischemia during percutaneous transluminal coronary angioplasty by transcatheter infusion of oxygenated fluosol DA 20%. *Circulation* 1986; 3:555–562.
57. Anderson HV, Leimgruber PP, Roubin SS, Nelson DL, Gruentzig AR. Distal Coronary

artery perfusion during percutaneous transluminal coronary artery angioplasty. *Am Heart J* 1985; 110:720–726.
58. Lehmann KG, Atwood JE, Snyder EL, Ellison RL. Autologous blood perfusion for myocardial protection during coronary angioplasty: A feasibility study. *Circulation* 1987; 76(2): 312–323.
59. Banka VS, Trivedi A, Patel R, Glusson M, Voci G. Prevention of myocardial ischemia during coronary angioplasty A simple new method for distal antegrade arterial blood perfusion. *Am Heart J* 1989; 118:830–836.
60. Stack RS, Quigley PJ, Collins G, Phillips HR III. Perfusion balloon Catheter. *Am J Cardiol* 1988; 61:776–806.
61. Farcot JC, Berland J, Bourdarias JP, Letac B. Physiologic anteroperfusion systems during balloon angioplasty: Experimental validation and clinical evaluation in single coronary disease patients (abstr). *J Am Coll Cardiol* 1990; 15(Suppl. A):249.
62. Weiner BH, Gore JM, Sloan KM, et al. Synchronized coronary sinus retroperfusion during LAD angioplasty. *J Am Coll Cardiol* 1986; 7:64A.
63. Costantini C, Sampaolesi A, Pieroni M, Pacheco G, Serna C, Belestrini C, Sala P, Neuburguer J, Conci E, Haendchen R, Corday E. Coronary venous retroperfusion support during high-risk coronary angioplasty in patients with acute ischemic syndromes (abstr). *J Am Coll Cardiol* 1989; II-625.
64. Berland J, Farcot JC, Barrier A, Dellac A, Gamra H, Letac B. Coronary venous synchronized retroperfusion during percutaneous transluminal angioplasty of left anterior descending coronary artery. *Circulation* 1990; 81(Suppl. IV):IV-35–IV-42.
65. Kar S, for the Investigators of the Multicenter Coronary Venous Retroperfusion Clinical Trial Group. Reduction of PTCA induced ischemia by synchronized coronary venous retroperfusion: Results of a multicenter clinical trial (abstr). *J Am Coll Cardiol* 1990; 15:250.
66. Vlietstra RE. Management of acute occlusion after percutaneous transluminal coronary angioplasty. *Eur Heart J* 1989; 10(Suppl. H):101–103.
67. Connor AR, Vlietstra RE, Schaff HV, Pechler JM, Pluth JR. Effect of clinical status after failed angioplasty on surgical morbidity and mortality (abstr). *J Am Coll Cardiol* 1987; 9:88.
68. Detre KM, Holmes DR, Holubkov R, Registry Investigators. Consequences of occlusion during PTCA: The 1985–1986 NHLBI PTCA Registry (abstr). *J Am Coll Cardiol* 1989; 13:230.
69. Meesman M, Karageuezian HS, Ino T, McGrath MF, Fishbein MC, Mandel MJ, Peter T. Selective perfusion if ischemic myocardium during coronary venous retroinjection: A study of causative role of venoarterial and venoventricular pressure gradients. *J Am Coll Cardiol* 1987; 10:887–897.

14. CLINICAL EXPERIENCE WITH THE HEMOPUMP LEFT VENTRICULAR ASSIST DEVICE

RICHARD K. WAMPLER AND RAYMOND A. RIEHLE

INTRODUCTION

An estimated 150,000 cases of cardiogenic shock occur each year in the United States. In spite of conventional therapy, which includes emergency revascularization, pharmacologic therapy, and intraaortic balloon pump counterpulsation, the reported mortality for cardiogenic shock is 80–90% [1–3]. The limited use of left ventricular assist devices (LVADs) in cases of cardiogenic shock has shown a significant potential to decrease mortality [4–11], however, the necessity for a major surgical procedure has confined the use of LVADs to postcardiotomy patients.

The goal of temporary mechanical circulatory assistance in the treatment of cardiogenic shock is to reduce the work of noncontractile but viable or "stunned" myocardium until ventricular contractility returns [12–15]. Temporary assist devices include a variety of experimental left ventricular assist devices (LVADs) [4,5,9,10,16–20], which are primarily adaptable to use in surgical patients, and the commercially available intraaortic balloon pump (IABP).

In the United States the IABP is widely used because it is readily available, easily implemented, and its use is associated with a relatively low risk. It is effective when treating mild to moderate cardiogenic shock. However, since it can only increase the cardiac output by about 15%, most patients with severe cardiogenic shock die when treated only with the IABP. Since synchronization is timed to the electrocardiogram, the IABP is ineffective in patients who suffer from moderate to severe dysrhythmia.

Postcardiotomy shock has been effectively treated with a variety of LVADs that are capable of taking over 80–100% of the cardiac work load [12,13,21]. Left ventricular assist devices have a significant advantage over the IABP in treating severe cardiogenic shock because of their ability to provide better hemodynamic support. Indeed, existing LVADs have demonstrated improved survival of patients suffering from postcardiotomy cardiogenic shock. Unfortunately, they have not been extensively used to treat cardiogenic shock secondary to acute myocardial infarction because of the associated risks and complexity of the devices.

A large nember of patients with cardiogenic shock need more circulatory assistance than can be provided by the IABP, but are not candidates for an LVAD. An intermediate device would benefit patients who fall in this therapeutic gap. A device that had the capability of the LVAD to support the majority of the hemodynamic work of the left ventricle, while exposing the patient to a degree of risk incumbent to the IABP, would be very useful clinically. However, widespread use of LVADs has awaited the development of a practical technology that can be implemented rapidly with minimal surgical risk and complications. The Hemopump is a catheter-mounted, peripherally introduced, mechanical assist device that is capable of supporting the majority of the circulatory requirements of a patient while providing a significant reduction in left ventricular work. This chapter presents an overview of the concept and operation of the Hemopump and the results of an ongoing trial evaluating the utility of the Hemopump in the treatment of cardiogenic shock. In addition, a pilot experience involving the use of the Hemopump for supported, high risk angioplasty is summarized. Finally, new horizons for use of a new 14 (Fr) percutaneous Hemopump as an interventional modality in the treatment of acute myocardial infarction to effect salvage of myocardium is discussed.

THE HEMOPUMP

The Hemopump is a new circulatory assist device capable of supporting the left ventricle without the need for a major surgical procedure [22,23]. In clinical trials, the Hemopump has shown promise in the treatment of cardiogenic shock and has been accompanied by acceptable risk. A description of the Hemopump, including the concept, operation, and results of clinical use, are discussed below.

System Description

The Hemopump is a temporary left ventricular assist device utilizing axial flow technology to draw blood out of the left ventricle and expel it into the aorta (Figure 14-1) [22]. The Hemopump can be placed via a peripheral vascular access and support up to 80% of the left ventricular work load. The Hemopump can provide up to 3.5 l/min of flow without the need for a contribution from the left ventricle or synchronization. Since the inflow cannula

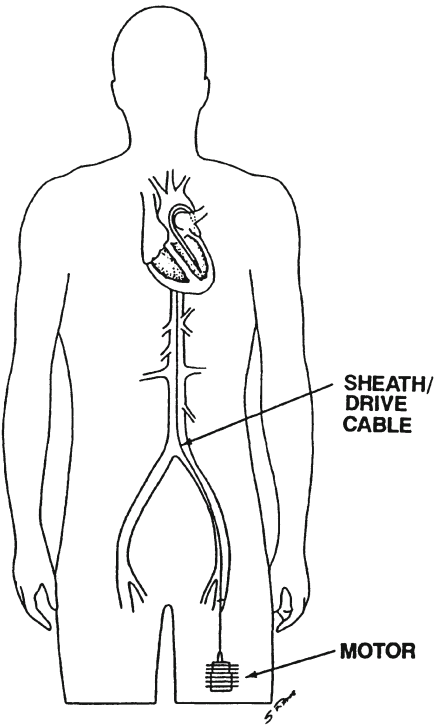

Figure 14-1. Anatomical placement of Hemopump.

is placed within the left ventricle, Hemopump assistance results in a significant degree of left ventricular decompression.

The pump (Figure 14-2) is contained within a 7-mm diameter (21 Fr), 16-mm long cylindrical housing. Attached distally to the pump housing is a 7-mm diameter by 26-cm long, curved inflow cannula. The inflow cannula resides in the left ventricle and the exhaust of the pump resides in the descending aorta. Proximal to the pump and inflow cannula is a 3-mm diameter (9.5 Fr) by 107-cm long, flexible drive cable housed in a polyurethane sheath. At the proximal end of the drive cable/sheath is a motor magnet that couples magnetically to a drive motor stator.

The console (Figure 14-3) is an integrated electronic controller incorporating all of the power, control, and diagnostic/alarm systems required to operate the pump and supply it with purge fluid. It also includes the roller pump that controls the delivery and collection rates of the purge fluid lubricant. The console has 30 minutes of battery backup.

Rotary motion is imparted to the pump drive by means of a magnetic coup-

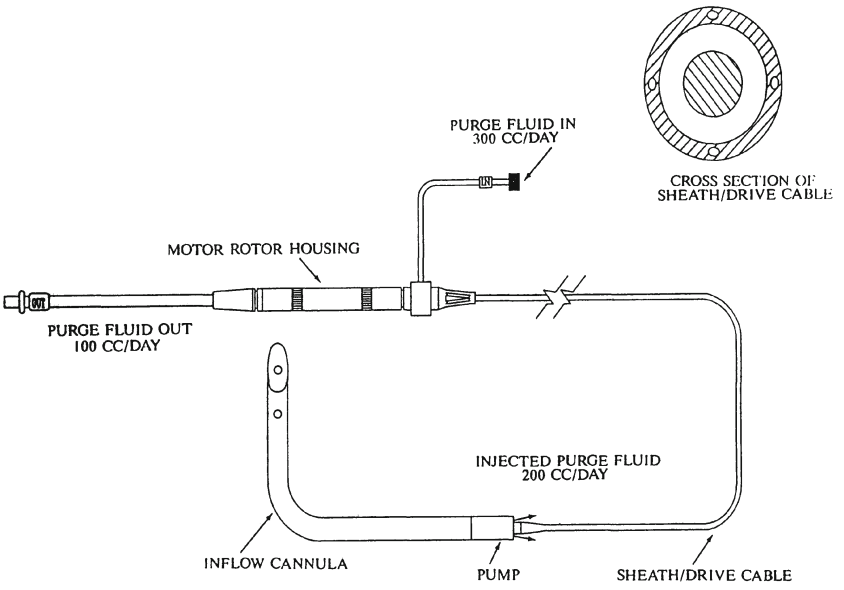

Figure 14-2. Schematic of the Hemopump.

ling, and is transmitted via a flexible drive cable to the pump rotor. Blood is removed from the left ventricle and expelled into the aorta as a result of the hydraulic gradient produced by the spinning pump rotor (Figure 14-4). The pump is a two-stage axial flow pump with a rotor (rotating blades of the pump) and a stator (nonrotating blades of the pump). With the pump spinning, blood flows from the tip of the cannula, across the rotor, and then across the stator into the systemic circulation.

Lubrication for the pump is provided by continuous infusion of 40% dextrose in water (D40W). Approximately 300 cc/day of D40W is pushed by a roller pump through purge tubing toward the pump via four outer lumens in the sheath. About 200 cc/day of the purge fluid flows across the seal into the patient and prevents blood elements from migrating into the pump. In addition, the dextrose lubricates the bearing surfaces and the flexible drive cable. The remaining 100 cc/day of the purge fluid is drawn away from the pump around the drive cable and motor magnet to a return bag, flushing cable-generated debris away from the pump.

Insertion procedure

The Hemopump system is set up on a sterile field with the entire pump, motor, and approximately 100 cm of purge tubing within the sterile field. A

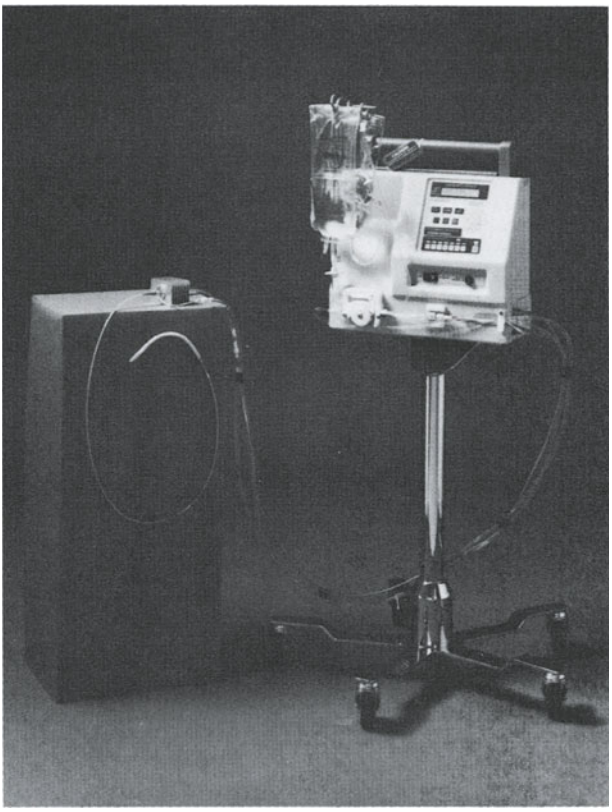

Figure 14-3. Hemopump system.

30-cm length of 12-mm graft is anastomosed end-to side to the insertion vessel. The Hemopump and a silicon graft plug (an 11.5-mm diameter by 20-mm long cylinder of silicon with a lengthwise hole the diameter of the drive cable sheath) is then inserted into the graft. The purpose of the graft plug is to maintain hemostasis while the pump/cannula is inserted.

There are three surgical approaches that can be used to insert the Hemopump. Initially the anastomosis of a 12-mm vascular graft to the insertion site on the artery was employed, but alternate methods have been employed [29]. The preferred approach is through the femoral artery. If the femoral artery is too small or is too severely atherosclerotic, an approach through the iliac artery is acceptable. In patients who have femoral and iliac vessels that are too small or too diseased for Hemopump insertion, a retroperitoneal approach through

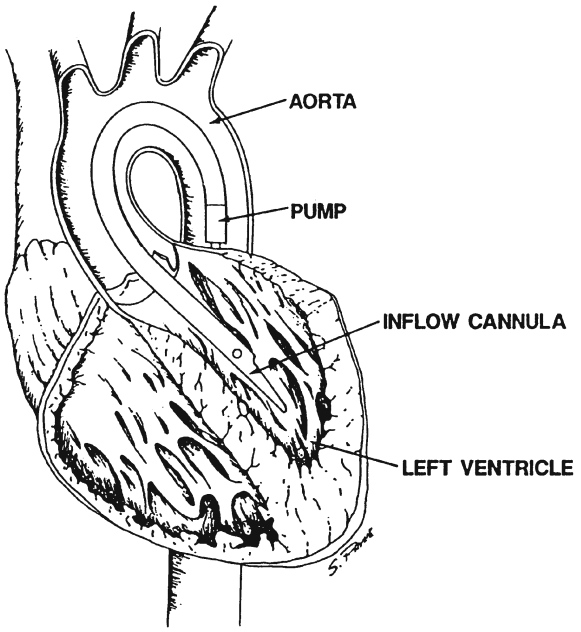

Figure 14-4. Position of Hemopump in the heart.

the abdominal aorta has been successful. With the use of the retroperitoneal approach, an 8-year-old child was successfully supported and weaned [26].

The patient is administered a heparin dose of 1–2 mg/kg prior to inserting of the pump into the artery. Once the pump is well into the abdominal aorta, it is turned on to a low speed. The pump is advanced through the aorta, around the aortic arch and across the aortic valve into the left ventricle. The insertion procedure is best performed under fluoroscopic visualization. Catheter guidance can be employed in cases where advancement of the cannula into the ventricle is difficult.

After proper position is established the pump is secured with the use of the silicone graft plug and the wound is closed with the drive cable exiting the lower margin. The Hemopump motor may be positioned on the patient's leg or on the abdomen.

CLINICAL TRIAL: CARDIOGENIC SHOCK

A clinical trial was conducted in the United States under an Investigational Device Exemption approved by the Food and Drug Administration. The purpose of this study was to evaluate the value of the Hemopump in the treatment of cardiogenic shock.

Patient selection

Eighty-seven patients with cardiogenic shock — defined as a cardiac index $<2.0\,l/min/m^2$, pulmonary capillary wedge pressure <18 mmHg, systolic blood pressure <90 mmHg **or** a *left ventricular work index* (LVWI) <1500 gm-$m/m^2/min$ and refractoriness to volume and pharmacologic therapy — were prospectively selected for treatment with Hemopump assistance. Sixty-six patients (58 males, 8 females) were supported for a mean time of 59.8 hours (range 1–194 hours). Cardiogenic shock was secondary to acute myocardial infarction in 25 (37.9%), failure to wean from cardiopulmonary bypass in 21 (31.8%), postcardiotomy shock in 10 (15.1%), and other etiologies in 10 (15.1%). The mean age was 54.3 years (range 8.6–80.0 years). Patients with significant blood dyscrasia, aortic prosthetic valve, severe aortic stenosis or regurgitation, or known dissecting aneurysm were not considered for Hemopump support. The intraaortic balloon pump had been used immediately prior to Hemopump insertion in 66.7% of the patients assisted [30]. Patients were maintained on heparin anticoagulation to a therapeutic range of 1.5–2.0 times control of either the activated clotting time or the partial thromboplastin time. Anticoagulation was not initiated in postsurgical patients until the cessation of active bleeding.

Hemodynamic and laboratory studies

Samples for analysis of plasma free hemoglobin, CBC, platelets, serum haptoglobin, and routine chemistries were drawn prior to pump insertion, during pump assistance, and after pump removal. Cardiac index, pulmonary capillary wedge pressure (PCWP), and systolic and mean blood pressure were recorded prior to pump insertion at selected intervals during pump assistance and following pump removal. Comparison of the mean of the cardiac index, PCWP, mean aortic pressure, and calculated left ventricular work index at preinsertion, during operation, and postremoval were then used to determine the hemodynamic response to Hemopump assistance.

The 30-day follow-up included physical and cardiologic examination, including functional status, echocardiography, complete blood count, platelets, and plasma free hemoglobin level. Postmortem examination was performed on 30 patients. Evidence of minor injury to the aortic valve was noted in one patient. No evidence of device related damage to cardiac structures or the aorta were recorded. Autopsy findings were consistent with the underlying disease state of the patients. No evidence of device relate systemic infarctions thought to be secondary to thromboembolism were documented in the autopsy reports.

CLINICAL TRIAL: SUPPORTED ANGIOPLASTY

The recent introduction of supported, high risk angioplasty with the use of percutaneous cardiopulmonary bypass support has resulted in a significant degree of acceptance and use in the catheterization laboratory [31,32]. The

potential benefit to selected patients who are poor candidates for surgical treatment and who were considered to have a high risk for angioplasty prompted the adaptation of the Hemopump to use in supported angioplasty.

Although the current, 21 Fr device is not percutaneously inserted, there are three potential advantages of the Hemopump when compared to support with percutaneous cardiopulmonary bypass:

1. The Hemopump requires only minimal anticoagulation relative to the level needed for cardiopulmonary bypass with an oxygenator, and a perfusionist is not needed.
2. If the patient suffers complications during the procedure, the patient can be safely supported for up to 7 days on the Hemopump.
3. The Hemopump provides significant left ventricular decompression in nearly all patients.

The first Hemopump supported angioplasty was reported by D. Loisance et al. [29] on eight patients. Patients were considered for supported PTCA if they met the following four criteria:

1. Evolving acute myocardial ischemia, unresponsive to medical therapy.
2. Ischemia related to a substantial stenosis with a patent distal runoff.
3. The patient was considered to have exceptionally high operative risk, or had been turned down for surgery.
4. The culprit lesion was present in the only patent vessel.

The Hemopump was placed using local anesthesia. The pump was introduced into the femoral artery without the use of an introduction graft. Blood loss during insertion was controlled by means of a special silicone rubber adapter fitted to the pump during insertion. The pump was advanced into the ventricle and assistance initiated prior to the angioplasty. No difficulty controlling the catheters in the presence of the Hemopump was encountered. Angioplasty was then performed while monitoring the electrocardiogram, hemodynamic status, and patient condition. The plasma free hemoglobin was measured after pump removal. The patient outcome from 3 to 7 months has been completed.

RESULTS OF CARDIOGENIC SHOCK TRIAL

Overall patient survival

Forty (60.6%) of Hemopump patients died on support or immediately after pump removal, 26 (39.4%) were successfully weaned from support, and 17 (25.8%) patients supported by the Hemopump survived to 30-day follow-up. Cardiogenic shock secondary to acute myocardial infarction demonstrated a survival of 8 of 25 (32.0%) compared to 5 of 21 (23.8%) for patients who could not be weaned from cardiopulmonary bypass, 1 of 10 (10.0%) for postcardiotomy shock, and 3 of 10 (30.0%) for other etiologies.

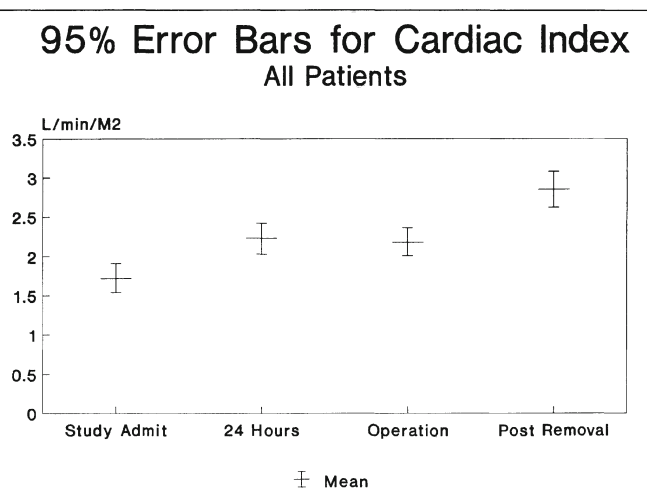

Figure 14-5. Cardiac index of patients in cardiogenic shock trial.

Hemodynamic changes on the Hemopump

The mean cardiac index (Figure 14-5) prior to pump insertion was 1.72 l/min/m^2. After 24 hours of operation the cardiac index rose to 2.27 l/min/m^2 ($p = .0005$). The mean cardiac index during pump operation was 2.31 l/min/m^2 ($p = .0001$). In patients who survived to weaning, the mean cardiac index was 2.76 l/min/m^2 ($p = .0002$).

The mean arterial blood pressure (MAP) prior to Hemopump insertion (Figure 14-6) was 56.92 mmHg; after 24 hours of assistance the MAP was 62.23 mmHg ($p = .034$). The MAP during pump operation was 65.45 mmHg ($p = .0002$). In patients who survived to weaning, the mean MAP was 105 mmHg ($p = .0001$). The mean preinsertion PCWP was 24.87 mmHg, and fell to 15.21 mmHg ($p = .0001$) after 24 hours of pump operation (Figure 14-7). The mean PCWP during operation was 15.92 mmHg ($p = .0001$). In patients who survived to weaning, the mean PCWP was 18.0 mmHg ($p = 0.0044$).

The left ventricular work index (Figure 14-8), or ventricular power, is calculated using the cardiac index (CI), PCWP, and MAP as follows:

$$\text{Left ventricular work index (LVWI)} = CI \times (MAP - PCWP) \times 13.6\,\text{g-m/m}^2\text{/min.}$$

The mean LVWI was calculable at pump insertion for 34 of 66 patients. Based on the Hemopump admission criteria, the calculated maximum LVWI for inclusion in the trial would have been 1500 g-m/m^2/min.

Prior to pump insertion, the LVWI (Figure 14-8) was 952 g-m/m^2/min, which rose to 1484 g-m/m^2/min ($p = .0005$) after 24 hours of operation. The

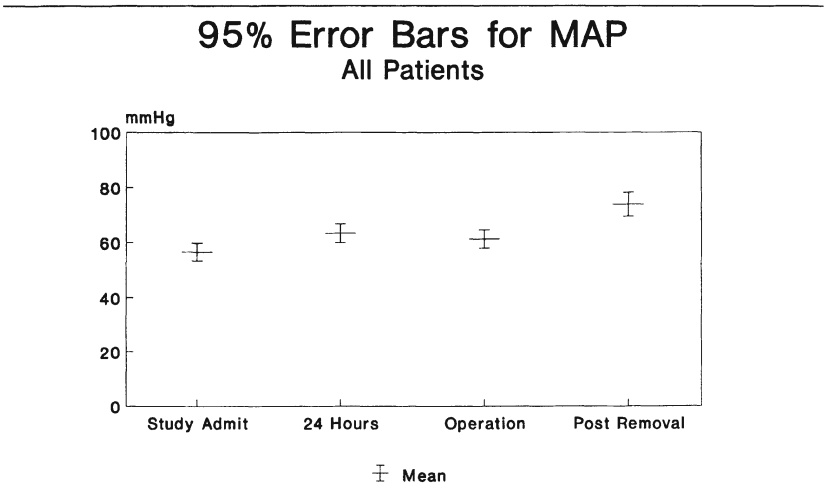

Figure 14-6. Mean arterial pressure of patients in cardiogenic shock trial.

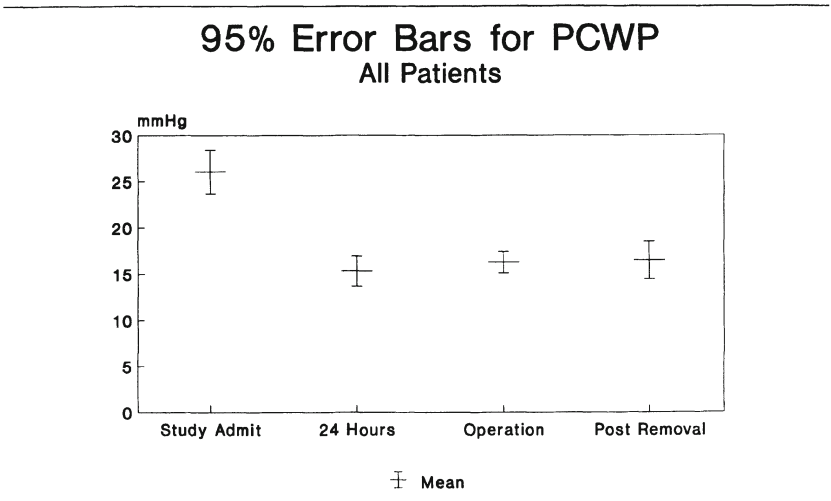

Figure 14-7. PCWP in cardiogenic shock patients. PCWP = pulmonary capillary wedge pressure.

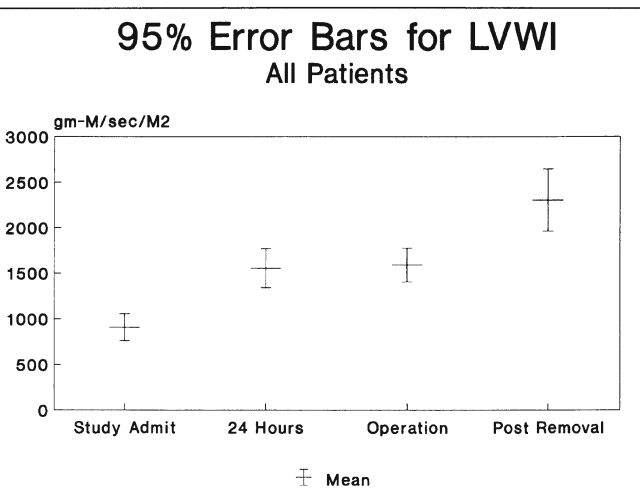

Figure 14-8. LVWI in cardiogenic shock patients. LVWI = left ventricular work index.

mean LVWI during operation was 1639 g-m/m^2/min ($p = .0001$). In patients who survived to weaning, the mean LVWI was 2210 g-m/m^2/min ($p = .0001$).

Effect on plasma free hemoglobin and platelets

Plasma free hemoglobin levels (Figure 14-9) at preinsertion, postinsertion, prior to pump removal, and at 30-day follow-up for all patients were measured. The mean level of plasma free hemoglobin during pump operation was 16 mg% for the nonsurgical group and 37 mg% for the failure to wean from cardiopulmonary bypass and postcardiotomy group. A transient minor rise was seen in most patients during the first 24 hours of operation, after which the level of plasma free hemoglobin stabilized for the duration of the pump assistance.

Platelet levels (Figure 14-10) for all surgical and nonsurgical patients were measured. The reduction in platelets occurring during Hemopump assistance was observed. The mean platelet level fell from 205,000/mm^3 to 110,000/mm^3 during operation. Thrombocytopenia was not associated with spontaneous bleeding. The platelet level returned to normal within 2 days of pump removal.

Complications and adverse events

The patient complications and adverse events during hospitalization are listed in Table 14-1. No patient death was reported to be a result of the Hemopump. No leg ischemia was observed.

One of the major safety concerns related to the use of the Hemopump was the potential for injury to blood cellular elements, particularly erythrocytes.

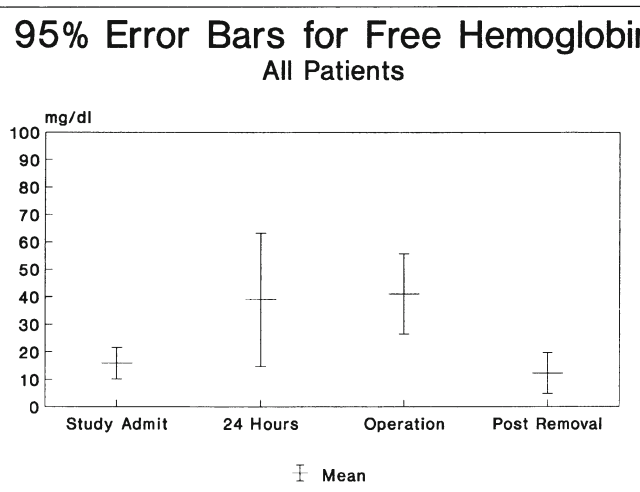

Figure 14-9. Plasma free hemoglobin of patients in cardiogenic shock trial.

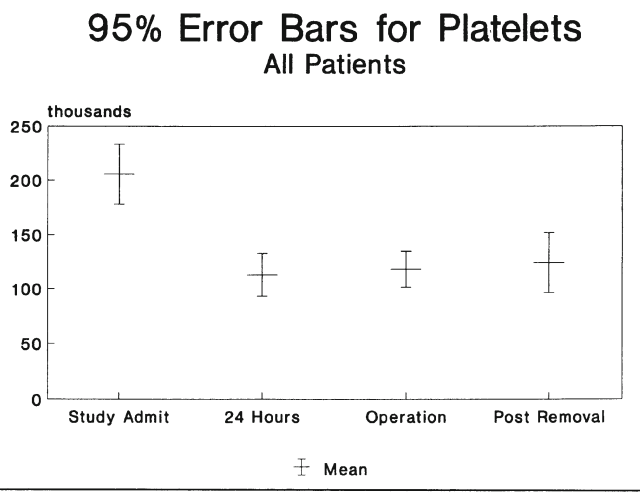

Figure 14-10. Platelet counts of patients in cardiogenic shock trial.

Normal levels are <15 mg% and elevations to 100–200 mg% can be observed following cardiopulmonary bypass. Plasma free hemoglobin is relatively nontoxic unless it precipitates in the renal tubules. The renal threshold for plasma hemoglobin is nominally 100 mg%. The mean levels of plasma free

Table 14-1. Adverse effects and complications

	Total		Residual deficit		Contributed to death	
	n	%	n	%	n	%
Device						
Unable to insert	21	24.1%	0	0.0%	0	0.0%
Hematologic						
Blood loss >500 cc	12	13.8%	0	0.0%	2	2.3%
DIC	2	2.3%	1	1.1%	0	0.0%
Hemolysis	8	9.2%	0	0.0%	0	0.0%
Thrombocytopenia	10	11.5%	0	0.0%	0	0.0%
Infections						
Septicemia	5	5.7%	0	0.0%	1	1.1%
Surgical site infection	1	1.1%	0	0.0%	0	0.0%
Vascular						
Ischemia	3	3.4%	1	1.1%	0	0.0%
Thromboembolism	9	10.3%	1	1.1%	1	1.1%
Vascular injury	6	6.9%	0	0.0%	0	0.0%
Other						
Cardiac arrest	2	2.3%	0	0.0%	0	0.0%
Death — operation	41	47.1%	0	0.0%	0	0.0%
Dysrhythmias	53	60.9%	0	0.0%	1	1.1%
Renal failure	7	8.0%	0	0.0%	2	2.3%

hemoglobin during hemopump operation were considered to pose a minimal risk to the patient.

Other complications

Thromboembolism

A total of nine embolic events were recorded in eight patients. A small renal infarction was found at postmortem exam in one patient and is likely to have occurred during pump operation. Two patients suffered hemiparesis after pump removal, associated with atrial fibrillation in one and preexisting mural thrombus in the other. A late femoral embolism was related to preexisting mural thrombus and was successfully managed with thrombectomy. The pump-related thromboembolism rate was 3.5%. A total incidence of systemic thromboembolism during and after pump operation was 10.5%. The incidence of thromboembolic events in patients suffering from acute myocardial infarction, mural thrombus, or undergoing LVAD implantation ranges from 5 to 15% [33,34,35,19].

Ventricular dysrhythmia

Patients undergoing open-heart surgery or suffering from myocardial infarction commonly present with ventricular ectopy and may develop ventricular tachycardia or fibrillation. The Hemopump cannula, representing a large

foreign body within the ventricular cavity, would be expected to produce a degree of ventricular ectopy. The clinical significance of ventricular ectopy and malignant rhythms relates to the hemodynamic compromise associated with these rhythms. It has been observed during the trials that cardiac output and mean arterial pressure are well maintained during periods of severe dysrhythmia during Hemopump assistance. Dysrhythmia observed include sustained ventricular tachycardia and on one occasion ventricular fibrillation. One patient was supported during ventricular fibrillation for 45 minutes. He was conscious during this episode and was successfully defibrillated.

Factors in favor of survival

Predictably, survival diminishes as the severity of illness increases. Thus, patient selection and early intervention would be expected to result in a significant increase of survival of patients in cardiogenic shock treated with the Hemopump. Calculated left ventricular work has been shown to have value as a prognosticator of survival in the setting of cardiogenic shock secondary to acute myocardial infarction and postcardiotomy shock.

Left ventricular work index (Figures 14-11 and 14-12)

The left ventricular work index prior to insertion is stratified and then com pared to the probability of surviving to weaning, and surviving to 30 days. Increasing preinsertion LVWI is associated with an increased probability of survival.

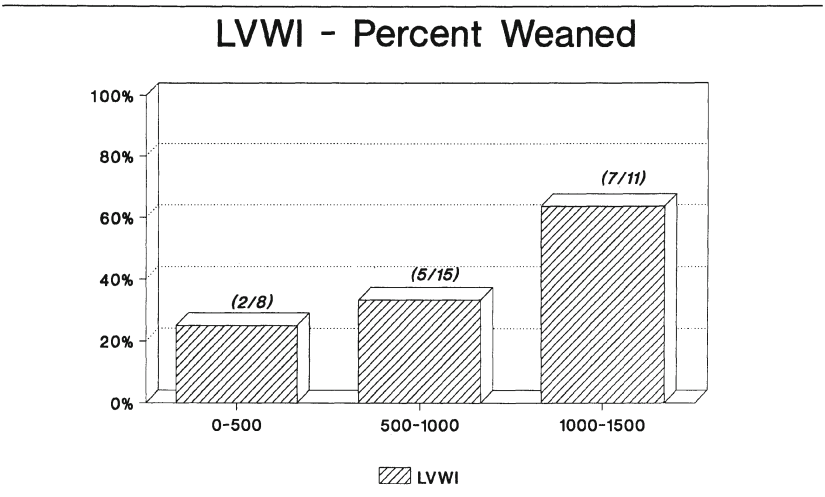

Figure 14-11. Survival to weaning as a function of preinsertion LVWI. LVWI = left ventricular work index.

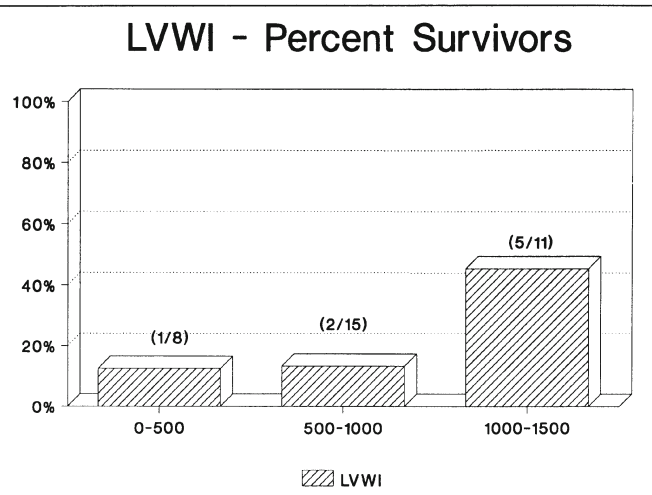

Figure 14-12. Survival to 30 days as a function of preinsertion LVWI. LVWI = left ventricular work index.

Cardiac index versus PCWP (Figure 14-13)

The prognosis after initiation of therapy can be evaluated after 24 hours of assistance. The figure is a display of cardiac index versus PCWP of all patients alive at 24 hours. It can be seen that 73% (11/15) of patients with a cardiac index >2.0 l/min/m^2 and a PCWP <18 mmHg after 24 hours of assistance survived to weaning. In the same group of patients 40% (6 of 15) survived to 30 days. Of the eight patients who died, only three died from cardiac causes. In the same group, two additional patients weaned with normal ejection fractions but later died of noncardiac etiologies.

RESULTS OF THE SUPPORTED ANGIOPLASTY TRIAL

The Hemopump was successfully placed in 5 of the 8 patients. Peripheral vascular disease precluded placement in three. Angioplasty was completed in the five supported patients. All of the supported patients tolerated their procedure well, in spite of significant arrhythmia and evidence of acute left ventricular dysfunction during dilation in four. Four of the five were symptom free under medical therapy at 3–7 months. The fifth patient was successfully revascularized after 3 weeks following improvement in permanent myocardial ischemia. Two of the three noninsertions died. One died during attempted angioplasty and the other after 10 days without intervention. The third noninsertion was taken to surgery after an organ donor became available and was successfully bypassed without the need for transplantation.

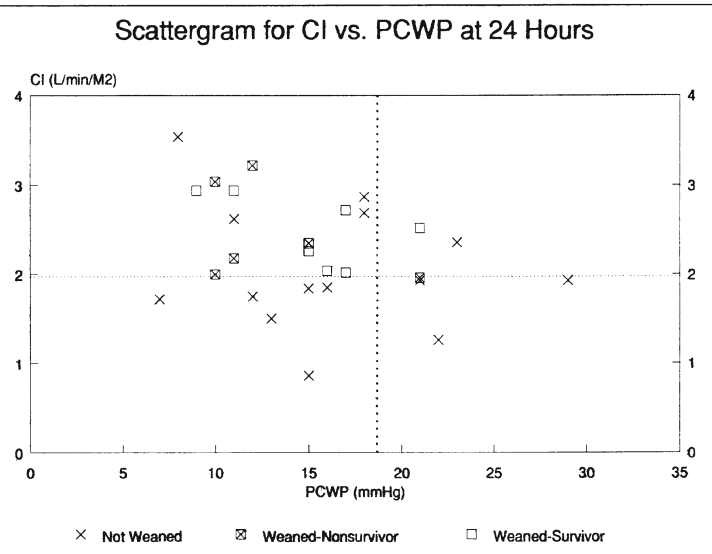

Figure 14-13. Survival as a function of CI and PCWP after 24 hours of assistance. CI = cardiac index; PCWP = pulmonary capillary wedge pressure.

Comments on the cardiogenic shock study

The clinical study has demonstrated the hemodynamic effectiveness and safety of the Hemopump when used in the treatment of cardiogenic shock. Hemopump therapy resulted in a significant decrease in pulmonary capillary wedge pressure, and an increase in the systolic blood pressure, cardiac index, and left ventricular work index. The hemodynamic effectiveness of the Hemopump resulted in a significant increase in patient survival in selected patients and was associated with acceptable risk. It is concluded that the Hemopump is an effective, safe, and practical left ventricular assist device and may play a significant role in the treatment of cardiogenic shock.

Comments on the supported angioplasty trial

Patients supported during angioplasty have demonstrated stable or improved hemodynamics during the procedure, even though arrythmia and left ventricular dysfunction was frequently observed during dilation. The Hemopump offers a new approach to the support of high risk patients during angioplasty and may offer advantages over current techniques.

NEW HORIZONS

Advances in Hemopump technology have supported the development of a smaller pump (14 Fr) that has been adapted to percutaneous, wire-guided

insertion. This device may be available in 1993 for investigational use; the ability to implement left ventricular assistance, percutaneously, in the cath lab will permit the cardiologist to adapt this modality early in the treatment of myocardial infarction.

The work of Buckberg et al. [36,37] suggests that the decompression of the ventricle during and following reperfusion significantly improves the salvage of myocardium in the area at risk. Smalling et al. [21,19,28,38] have shown that the Hemopump, during acute occlusion of the LAD in dogs, results in a significant reduction in left ventricular work, improvement in myocardial perfusion in the area at risk, and improves recovery of the myocardium in the area at risk. Similar unpublished work by Scht in Germany and Flemming in Brussels has shown a significant reduction in myocardial oxygen consumption and favorable shifts in lactate production in response to Hemopump assistance during ligation of the LAD. Physiologically, such a benefit might be predicted, based on the ability of the Hemopump to reduce left ventricular work and myocardial O_2 consumption, and to increase coronary perfusion.

Thus, mechanical assistance may be employed in the treatment of acute coronary occlusion to minimize the loss of myocardium in the area at risk. The clinical utility of such an application can only be defined after completion of human clinical trials designed to evaluate the efficacy of such a therapy.

CONCLUSIONS

The ability to support the circulation and reduce left ventricular work may significantly benefit patients with cardiogenic shock and its complications. At the present time, the technological innovation of the Hemopump provides a unique and practical means of beginning to understand the role of mechanical assistance in the treatment of cardiogenic shock and acute myocardial infarction. The initial clinical trial, treating cardiogenic shock has been most encouraging. Pilot experience with supported angioplasty has been promising. The limitations of the 21 (Fr) device have spawned the development of a percutaneously inserted device that may find broad application in the treatment of acute myocardial infarction. The role of this evolving technology in clinical therapy will be defined as a result of continuing clinical study.

REFERENCES

1. Parmley W. Cardiac failure. In Rosen MR, Hoffman BF, eds. *Cardiac Therapy*, Martinus Nijhoff Publishers, Boston, 1983; pp. 21–44.
2. Schoen FJ, Palmer DC, Bernhard WF, et al. Clinical temporary ventricular assist. *J Thorac Cardiovasc Surg* 1986; 92:1071–1081.
3. Shoemaker WC, Bland RD, Appel PL. Therapy of critically ill postoperative patients based on outcome prediction and prospective clinical trials. *Surg Clin North Am* 1985; 65(4):811–833.
4. Campbell CD, Tolitano DJ, Weber KT, Statler PM, Replogle RL. Mechanical support for postcardiotomy heart failure. *J Cardiac Surg* 1988; 3:181–191.
5. Golding LR, Jacobs G, Groves LK, Gill CC, Nose' Y, Loop FD. Clinical results of mechanical support of the failing left ventricle. *J Thorac Cardiovasc Surg* 1982; 83:597–601.

6. Kantrowitz A, Wasfie T, Freed P, Rubenfire M, Wajszczuk W, Schork MA. Intraaortic balloon pumping 1967 through 1982: Analysis of complications in 733 patients. *Am J Cardiol* 1986; 57:976–983.
7. Maccioli GA, Lucas WJ, Norfleet EA. The intraaortic balloon pump: A review. *J Cardiothorac Anesth* 1988; 2(3):365–373.
8. McEnany MT, Kay HR, Buckley MR, et al. Clinical experience with intraaortic balloon pump support in 728 patients. *Circulation* 1978; 58:122–132.
9. Pae WE, Pierce WS, Pennock JL, Campbell DB, Waldhausen JA. Long-term results of ventricular assist pumping in postcardiotomy cardiogenic shock. *J Thorac Cardiovasc Surg* 1987; 93:431–441.
10. Pennington DG, Samuels LD, Williams G, et al. Experience with the Pierce-Donachy ventricular assist device in postcardiotomy patients with cardiogenic shock. *World J Surg* 1985; 9:37–46.
11. Pennington DG, Swartz M, Codd J, Merjavy J, Kaiser G. Intraaortic balloon pumping in cardiac surgical patients: A nine-year experience. *Ann Thorac Surg* 1983; 36(2):125–131.
12. Laas J, Campbell CD, Takanashi Y, Replogle RL. Oxygen consumption of the left ventricle during transapical left ventricular bypass. *J Thorac Cardiovasc Surg* 1980; 80(2): 280–288.
13. Lass J, Campbell CD, Takanashi Y, Pick R, Replogle RL. Preservation of ischemic myocardium with TALVB using complete left ventricular decompression. *Trans Am Soc Artif Intern Org* 1979; 25:220–223.
14. Maroko PR, Bernstein EF, Libby P, et al. Effects of intraaortic balloon counterpulsation on the severity of myocardial ischemic injury following acute coronary occlusion. *Circulation* 1972; 14:1150–1159.
15. Takanashi Y, Campbell CD, Laas J, Pick RL, Meus P, Replogle RL. Reduction of myocardial infarct size in swine: A comparative study of intraaortic balloon pumping and transapical left ventricular bypass. *Ann Thorac Surg* 1981; 32(5):475–485.
16. Bernstein EF, Dorman FD, Blackshear PL, Scott DR. An efficient, compact blood pump for assisted circulation. *Surgery* 1970; 68(1):105–115.
17. Farrar DJ, Hill JD, Gray LA, et al. Heterotopic prosthetic ventricles as a bridge to cardiac transplantation. *New Eng J Med* 1988; 318:333–340.
18. Magovern GJ, Park SB, Maher TD. Use of a centrifugal pump without anticoagulants for postoperative left ventricular assist. *World J Surg* 1985; 9:25–36.
19. Pae WE, Pierce WS. Combined registry for the clinical use of mechanical ventricular assist pumps and the total artificial heart: Third official report — 1988. *J Heart Transp* 1989, in press.
20. Pennington DG, Merjavy JP, Swartz MT, Willman VL. Clinical experience with a centrifugal pump ventricular assist device. *Trans Am Soc Artif Intern Organs* 1982; 28:93–99.
21. Merhige ME, Smalling RW, Cassidy D, Barrett R, Wise G, Short J, Wampler RK. Effect of the Hemopump left ventricular assist device on regional myocardial perfusion and function: Reduction of ischemia during coronary occlusion. *Circulation* 1989; 80(Suppl. III):158–166.
22. Wampler RK, Moise JC, Frazier OH, Olsen DB. In vivo evaluation of a peripheral vascular access axial flow blood pump. *ASAIO Trans* 1988; 34:450–454.
23. Butler KC, Moise JC, Wampler, RK. The Hemopump: A new cardiac prothesis device, *IEEE Trans Biomed Engin*, in press.
24. Frazier OH, Duncan JM, Nakatani T, Parnis SM, Fuqua JM. Clinical experience with the Hemopump (abstr). *ASAIO* 1989; 35:17.
25. Frazier OH, Wampler RK, Duncan JM, Dear WE, Macris MP, Parnis SM, Fuqua JM. First human use of the Hemopump, a catheter-mounted ventricular assist device. *J Am Coll Cardiol* 1989; 13(2):121A.
26. Frazier OH, Macris MP, Wampler RK, Duncan JM, Sweeney MS, Moncrief CL, Fuqua JM. Treatment of cardiac allograft failure by use of an intraaortic axial flow pump. *J Heart Transpl* 1989; 8:110.
27. Rutan PM, Rountree WD, Myers KK, Barker LE. Initial experience with the Hemopump. *Crit Care Nurs Clin North Am* 1989; 1(3):527–534.
28. Smalling RW, Sweeney MJ, Cassidy DB, Barrett RL, Morris RE, Lammermeier DE, Key PG, Haynie MP, Frazier OH, Wampler RK. Hemodynamics in cardiogenic shock after acute myocardial infarction with the Hemopump assist device. *Circulation* 1989; 80(4):II-624.
29. Loisance D, Dubois-Rande JL, Deleuze P, Okude J, Rosenval O, Geschwind H. Prophylactic intra ventricular pumping in high risk coronary angioplasty. *Lancet* 1990; 335(24):438–440.

30. Norman JC, Cooley DA, Igo SR, et al. Prognostic indices for survival during postcardiotomy intraaortic balloon pumping. *J Thorac Cardiovasc Surg* 1977; 74(5):709–720.
31. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Percutaneous cardiopulmonary bypass support in high risk patients undergoing percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1989; 64:1258–1268.
32. Shawl FA. Percutaneous cardiopulmonary bypass support in high risk interventions. *J Invas Cardiol* 1989; 5:287–293.
33. Bergentz, SE, et al. Incidence of thromboembolism in association with surgical and medical diseases. *Acta Chir Scand* 1988; 543(Suppl.):10–14.
34. Chesebro JH, et al. Intracardiac thrombi and systemic thromboembolism; detection, incidence, and treatment. *Ann Rev Med* 1985; 36:579–605.
35. Haugland JM, et al. Embolic potential of left ventricular thrombi detected by two-dimensional echocardiography. *Circulation* 1984; 70(4):588–598.
36. Okamoto, Buckberg, et al. Studies of controlled reperfusion after ischemia VIII. Regional blood cardioplegic reperfusion during total vented bypass without thoracotomy: A new concept. *J Thorac Cardiovasc Surg* 1986; 92:553–563.
37. Allen, Buckberg, et al. Studies of controlled reperfusion after ischemia XIII. Reperfusion conditions: Critical importance of total ventricular decompression during regional reperfusion. *J Thorac Cardiovasc Surg* 1986; 92:605–612.
38. Smalling RW, Cassidy DB, Merhige M, Felli PR, Wise GM, Barrett RL, Wampler RK. Improved hemodynamic and left ventricular unloading during acute ischemia using the Hemopump left ventricular assist device compared to intraaortic balloon counterpulsation. *J Am Coll Cardiol* 1989; 13(2):160A.

INDEX