Clinical Guide to Principles of Fiber-Reinforced Composites in Dentistry

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Clinical Guide to Principles of Fiber-Reinforced Composites in Dentistry

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Preface

This book on fiber-reinforced composites (FRC) covers the current understanding and knowledge on the properties of FRCs and describes why and how the FRCs became an essential group of dental biomaterials. We have studied FRC materials since the early 1990s and have published a significant number of scientific papers. This book summarizes the most relevant data from in vitro and clinical studies accomplished on this topic.

Completion of this book was an important milestone for us after almost 30 years of scientific and clinical work, since the commercialization of glass FRCs used in dentistry 20 years ago. Starting research on a topic that was barely investigated from dental or medical perspectives in the late 1980s, and seeing the increased scientific interest in the material over the years and, most importantly, receiving feedback from clinicians throughout the world on the importance of FRC materials, have motivated us to write this book. Many recognized scientist colleagues and postgraduate students have contributed to the scientific work compiled over the years. It was fascinating for us to see the results of the scientific work being translated into clinical applications over the years that have delivered numerous benefits to patients who need dental and medical treatments using such biomaterials.

We are grateful to all coworkers who have contributed to the demanding work investigated in this book. Industrial and academic partners in this research area are also highly appreciated. We acknowledge Elsevier for taking on the task of publishing this book.

We hope that the readers of this book will gain background information and learn new aspects on how to best utilize FRC materials in their daily clinical practices.

Pekka Vallittu and Mutlu Özcan
March 19th, 2017

Rationale

Traditional dental materials such as metals and ceramics, beside their several good properties, have a number of disadvantages such as significant damage of dental hard tissues caused by grinding to make space for metal and ceramic crowns and fixed dental prostheses. There has also been concern about releasing metal ions from restorations, which can be potentially harmful. On the other hand, development of restorative and prosthetic dentistry, i.e., reconstructive dentistry, has moved to more often use adhesively retained restorations rather than relying only on mechanically interlocked restoration systems. Fiber-reinforced composites (FRCs) are a novel group of dental materials characterized by fibrous fillers, which are being increasingly used in place of traditional prosthodontic materials. They allow use of minimally invasive adhesive tooth-colored restorations with lightweight but durable and biocompatible materials.

Why use FRCs in dentistry? Although there are several proven dental materials and treatment options based on conventional dental materials, a large number of partially edentulous patients are not treated by fixed dental prostheses to replace their missing teeth. This is often due to the high cost of the current type of fixed prostheses treatments, and the irreversible damage that the treatment causes when creating space for metal and ceramic crowns by grinding abutment teeth. Additionally, in some cases medical reasons do not allow for the use of bone anchoring implants in treatment. On the other hand, other nonmetallic alternative materials such as zirconia have become available, but unfortunately when zirconia is used, equal amounts of reduction of abutment tooth substance is needed as when using conventional porcelain-fused-to-metal restorations. Furthermore, large numbers of removable dentures face breakage of acrylic resin parts, and metal wires and meshes incorporated to the resin have not been able overcome the recurrent breakages. At the moment, the only material group that can be used by direct technique to reach high load-bearing capacity restorations, e.g., for fixed dental prostheses, is FRC. The use of FRCs in clinical dentistry is part of value-based medicine, which integrates evidence-based medicine and patient-perceived quality-of-life improvement. This book provides clinicians and students with a hands-on guide to the use of FRCs within dentistry.

Introduction

Dental fiber-reinforced composites (FRCs) have been studied and developed since the 1960s (Smith, 1962), although breakthroughs in the research happened in the early 1990s (Ladizesky, 1990; Vallittu and Lassila, 1992; Vallittu, 1993; Ladizesky et al., 1994; Freilich et al., 1998; Loose et al., 1998). Manmade high aspect ratio fillers of fibers have been used since ancient times to reinforce bricks and buildings. Modern FRCs have diverse applications such as the airspace industry, sport industry, and car industry, where high static and dynamic strength and fracture toughness, especially in relation to weight, are desired properties. Dental and medical devices are typically subjected to repeated loading cycles by the masticatory system or by the weight of the body during physical exercise. FRCs are typically designed to have the highest possible reinforcing efficiency against the direction of stress, and with this in mind, they often represent an anisotropic material in terms of their mechanical properties (Vallittu, 2016). Additionally, some other clinically important properties such as optical, surface, chemical, and physical, thermal, and polymerization contraction are related to the direction and alignment of fibers in the FRC. From the point of view of materials science, FRCs are a material group of choice for dental and medical needs. At the moment FRCs are used in fixed prosthodontics, restorative dentistry, periodontology and orthodontics in various applications (Meiers et al., 1998; Rantala et al., 2003; Le Bell et al., 2004; Vallittu, 1998; Narva et al., 2001; Behr et al., 2001; Bergendal et al., 1995; Özcan et al., 2005; Sewón et al., 2000).

Dental reconstructive devices have been made for hundreds of years from materials such as metal, and in the twentieth century also from synthetic inorganic and organic materials, including ceramics and resin-based materials. This has been happening through the development of biomaterials since they were first established as a scientific discipline, and it has been strongly related to the development and way of using materials in dentistry. On the other hand, from the perspective of modern materials science, one can conclude that only limited development has occurred in dental reconstructive materials. For example, reconstructive dentistry has utilized practically only bulk isotropic materials such as metals, ceramics, polymers, and resin composites. Only recently have the first steps been taken towards tailoring the properties of materials towards being anisotropic rather than isotropic (Vallittu, 2014). The structural designs of elements in natural materials are to a large extent based on fibrous materials (Naleway et al., 2015). Fibrous materials provide high tensile strength to the structure, typically in the direction of the fibers. The engineering sciences have successfully used reinforcing fiber systems, which have their structural origins in tissues like bone and dentine or wood. Engineers weave the synthetic reinforcing fibers into fabrics in order to reinforce construction in multiple directions.

The dental treatment approach, which beneficially utilizes the versatile properties of FRCs, is called the "dynamic treatment approach," where the restorative and prosthetic treatment starts with minimal intervention and, only if needed, heavier and more destructive conventional prosthodontic treatments will be used later in the patient's life. This book aims to provide state-of-the-art knowledge in the field of using FRC materials in clinical dentistry and to share basic materials science background for the successful use of FRCs.

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Key requirements for dental FRCs

1

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Chapter Outline

1.1 Introduction: The Oral Environment

The oral environment, where dental constructs and devices are used, is host to various different hostile features of the masticatory system (Vallittu and Könönen, 2000). The oral cavity is the first part of digestive canal, with the additional functions of communication both phonetically and through gesture. As part of the digestive canal, the oral cavity places demands on dental biomaterials and restorations, both mechanically and chemically. Dentition also plays a significant role in the articulation of sounds. In the context of humans, dentition as a part of the oral cavity is of importance for social wellbeing. The natural appearance of teeth in terms of color shade, surface texture, and basic shape of the teeth, has important culturally-related meaning for humans. In the modern world, patients are well aware of the possibilities of dental treatments and how they can fulfill the needs of function and appearance (Vallittu et al., 1996). Another critical aspect of dental biomaterials and restorations relates to temporal properties. The ageing of restorations of whatever material changes the physical and other materials' properties (Eliades et al., 2003). Adequate mechanical strength, high surface gloss, and good resistance against wear are examples of requirements for dental restorations. Additionally, biological aspects of biofilm adsorption of proteins and microbes contribute to longevity of restorations, adjacent tissues, and treatment outcome. Complexity of the oral environment, in combination with the complex multiphasic dental biomaterials and dental devices in restorative and prosthetic dentistry, challenges the dental profession in its aim for long-lasting treatment outcomes.

One important aspect of longevity of treatment outcome relates to the accumulation of oral microbes on the surface of dental constructs and dental tissues.

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Accumulation and colonization of microbes involves adherence of microbes to the substrate (Douglas, 1985). When a dental material or device is exposed to the oral cavity, a noncellular acquired biofilm covers the material surface by adsorption of extracellular molecules of glycoproteins and proteoglycans, which influences the attachment of cells to the surface. In some cases there can be continuous process of biofilm adsorption-desorption, but in the oral cavity adsorption dominates and causes accumulation of plaque on the material surface. Material properties like surface free energy, hydrophilicity, and surface texture influence adhesion of microorganisms. Rough surfaces and those having high surface energy are both known to adsorb more microbial biofilm on the surface than smooth and low energy surfaces (Glantz, 1971; Quirynen and Bollen, 1995). Surface roughness and surface texture is considered both macroscopically and ultrastructurally. Macroscopic textures are responsible for the aggregation of particulates of the biofilm, whereas ultrastructural features have more importance for the microstructural attachment of the biological components of biofilm, including parts of microbes. Any surface which is exposed in the oral cavity is covered instantly with a salivary biofilm called acquired pellicle, which has several functions, but may also promote the adhesion of certain microbes.

One of the key pathogenic microorganisms in relation dental diseases and reconstructive treatments outcome is *Streptococcus mutans*. There is existing information on how *S. mutans* behave on the surface of different kinds of dental materials, including fiber-reinforced composites (FRCs) with various kinds of reinforcing fibers (Tanner et al., 2000, Tanner et al., 2001). Adherence of *S. mutans* is related also to the presence of proteins and some other microorganisms, such as *Candida albicans*. Out of FRC materials, glass FRC binds the least amount of *S. mutans* to the surface, and ultra high molecular weight polyethylene (UHMWP) fibers bind the highest amounts of microbes to the surface (Fig. 1.1). This was confirmed also by a clinical study of plaque accumulation on the surface of various dental materials (Tanner et al., 2003). Studies where denture base polymers have been reinforced with glass fibers showed that the glass fibers running along the surface of the palatal plate of the denture do not enhance the growth of *C. albicans* on the denture base material (Waltimo et al., 1999). This has been confirmed both with the heat-cured and autopolymerized denture base polymer of polymethylmethacrylate. Thus, if the glass fibers are exposed during polishing of the denture, the reinforcing material of glass fibers appears not to increase the adherence of this common microbe. Despite the relatively low microbial adherence to the glass FRC, it is recommended to cover the FRC with particulate filler resin composite, and in the removable denture, with a layer of acrylic resin, which allows better surface gloss and natural-looking appearance for the restoration (Tanner et al., 2001). However, the surface coverage of the FRC with particulate filler resin composite does not influence to the water absorption of the material over time, which affects some physical properties of the resin composite over time. Water diffuses into the polymer matrix with simultaneous leaching of curing reaction residuals (residual monomers, oxidation products of initiators and activators) of the polymer matrix regardless of the surface coverage.

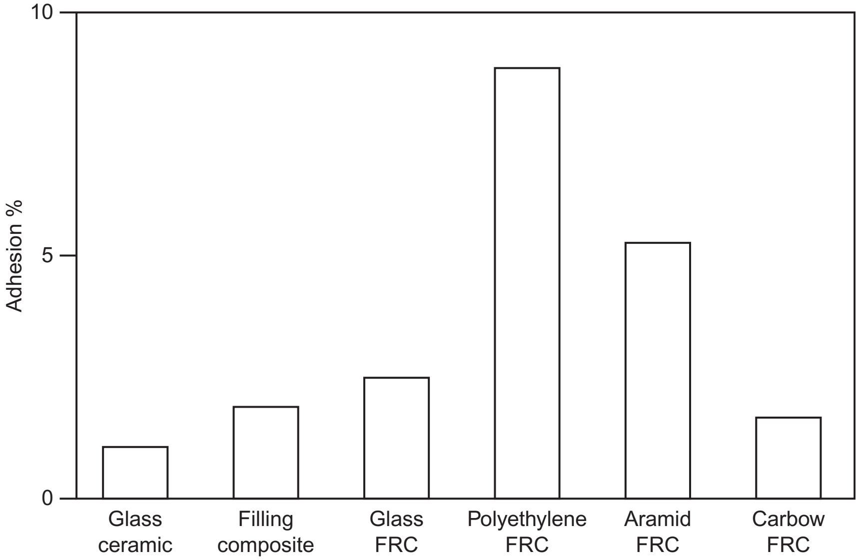

Figure 1.1 Relative adsorption of *S. mutans* on the surfaces of different dental materials (Tanner et al. 2002).

In a wider perspective of the goals of dentistry, the oral environment should also be understood as a field where host defense mechanisms and threats by pathogens are competing and can provoke leaching of dental hard tissues but also human-made materials. Pathogenic oral microbes of, e.g., *S. mutans* and *Lactobacillus* are well known to produce acids which locally can lower the pH of the tooth surface to the level of 5.4–4.4, which is a critical value, where significant amounts of enamel are dissolving. Thus, although the polymer matrix of the FRC protects the fibers from the direct influence of decreasing pH, the FRC, and more precisely reinforcing fillers and their adhesive interfaces, could be prone to the leaching and degradation. This means that individual treatment entity of existing teeth or parts of teeth in combination with restorations made by dental professionals is in the best-case scenario long-lasting results; but they may be damaged earlier than expected for several reasons. The oral environment needs restorations to be easily adjusted, modified, repaired and renewed when needed. The importance of the dynamic nature of the loading conditions in the oral cavity with existing high static loads has been understood for a long time as a key aspect for biomechanical longevity of dental restorations (Johnson and Matthews, 1949).

1.2 Mechanical Loads Faced by FRCs

Biomechanically, the loading conditions in the oral cavity are demanding, as has been described previously (Vallittu and Könönen, 2000). Oral biomechanics originate from the function of the muscles of the masticatory system and their application of force to teeth and restorations, and finally to periodontal tissues and jawbones. Forces are controlled or modulated by the sensory apparatus of teeth and adjacent periodontal tissues. Prosthodontic and restorative devices must be designed to resist the same magnitude of forces as intact natural teeth. Prosthesis requires both static and dynamic strength as well as a number of other mechanical properties in order to resist the necessary transmission of forces over the many years in the mouth. Maximal biting forces measured unilaterally may be as high as 850 N, but in normal mastication function, forces are considerably lower, around 50−80 N (Waltimo and Könönen, 1995). When the number of natural teeth decreases, the maximal biting force also lowers. Thus, a patient who is wearing removable partial dentures in both jaws has maximal biting force of 300 N, whereas a complete denture wearer has forces of 180 N (Lassila et al., 1985).

The direction of biting force needs to be considered carefully because FRCs are generally not isotropic (independent of direction of applied load), but rather are often anisotropic (different depending on the direction of the applied loads). Anisotropicity of FRC plays a significant role in planning and designing devices used in dentistry, since the loading conditions defined by the masticatory system produce loads and stresses of various magnitudes and types (bending, shear, tensile, compression, torque). These aspects are described more in detail in other chapters of this book.

Teeth and dental restorations are affected by masticatory forces, which vary depending on the position of a tooth. Strength and modulus of elasticity are parameters that describe the static mechanical properties of a material. This is especially important when FRCs is used in combination with other materials. When external force such as biting force is transmitted to the tooth or restoration, the materials are said to be in a state of stress, i.e., the energy from force and counterforce is stored in the material. Materials respond to stress by straining which is seen by changes in the shape and dimensions of the material. Stress can be tensile, compressive, shear, or torsional in type; all of which are present in oral conditions (Fig. 1.2).

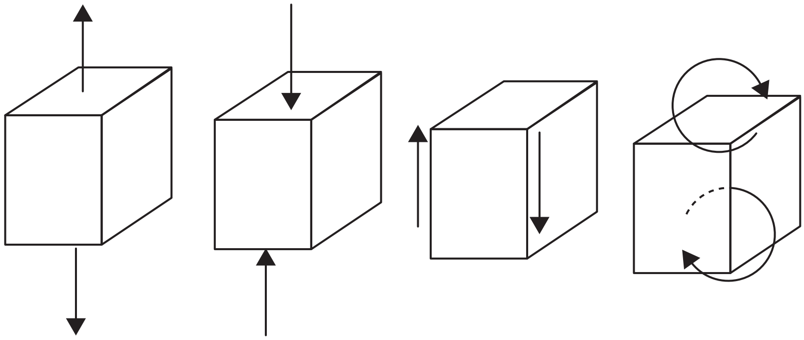

Figure 1.2 Type of stress affecting the material (from the left: tensile stress, compression stress, shear stress, and torsional stress). The arrow shows the direction of external force.

Tensile stresses typically cause fracture to restorations, whereas shear stress typically causes debonding of restorations like resin bonded fixed dental prostheses from the surface of enamel. Design of the restoration, especially of fixed dental prostheses, but also of crowns, inlays, and onlays, must follow principles that reduce the amount of stress of any kind which can damage or loosen the construction. In fixed dental prostheses the distance from one abutment to another abutment, i.e., the span length of the fixed dental prostheses and height of the connector part of the prostheses, greatly influences the magnitude of stress, which can deflect and finally break the construction. All attempts to diminish the magnitude of deflection should be made. One of the most important is correct dimensioning of the connector, and selecting high strength and tough material for fixed dental prostheses. The resistance to deflection of two-end supported span is as follows (Vallittu and Könönen, 2000):

$$\text{Deflection} = \frac{F \times l^3 \times c}{E \times w \times h^3}$$

where F is the force, l the length of the span, c a material constant, E the modulus of elasticity, w the dimension of the object perpendicular to the applied load, and h the dimension parallel to the direction of the load.

When two-end supported span like a three unit fixed dental prostheses is loaded, the tensile stress occurs on the lower surface of the material sample, i.e., the surface closest to the alveolar crest of fixed dental prostheses. Crown margins of abutments are also affected by tensile stress and are typical areas where cracks start to propagate. In the case of one-end supported span (cantilever type of fixed dental prostheses) the tensile stress is concentrated on the upper surface, i.e., the occlusal surface (Fig. 1.3). It needs to be emphasized that the height of the connector plays an important role in eliminating the deflection of the construction. In material properties, modulus of elasticity is also an important factor in this respect. In bilayered material structures where the FRC framework is covered from oral surfaces with veneering resin composite, the stress distribution may be different. In bilayered material structures the interfacial adhesion of layers, as well as the ratio of the layer thickness, has a significant role in the mechanical behavior of the composite structure (Garoushi et al., 2006).

Significant biting forces are not developed until teeth are in contact. Chewing forces are lower than maximal biting forces. It has been stated that any dental restoration in the molar region should withstand 1000 N static load. Maximum occlusal load may be applied to teeth 3000 times per day, resulting in a considerably high number of loading cycles annually (Johnson and Matthews, 1949). This puts the strength requirements of the fixed dental prostheses and other restorations into the perspective that static strength and load bearing capacity is not the only important property. The prostheses and restoration should also withstand a considerable number of repeated loading cycles. Thus, the fatigue resistance of the material and restoration also needs to be high. Out of other dental materials, ceramics are typically lacking in high toughness, and therefore they are more sensitive to

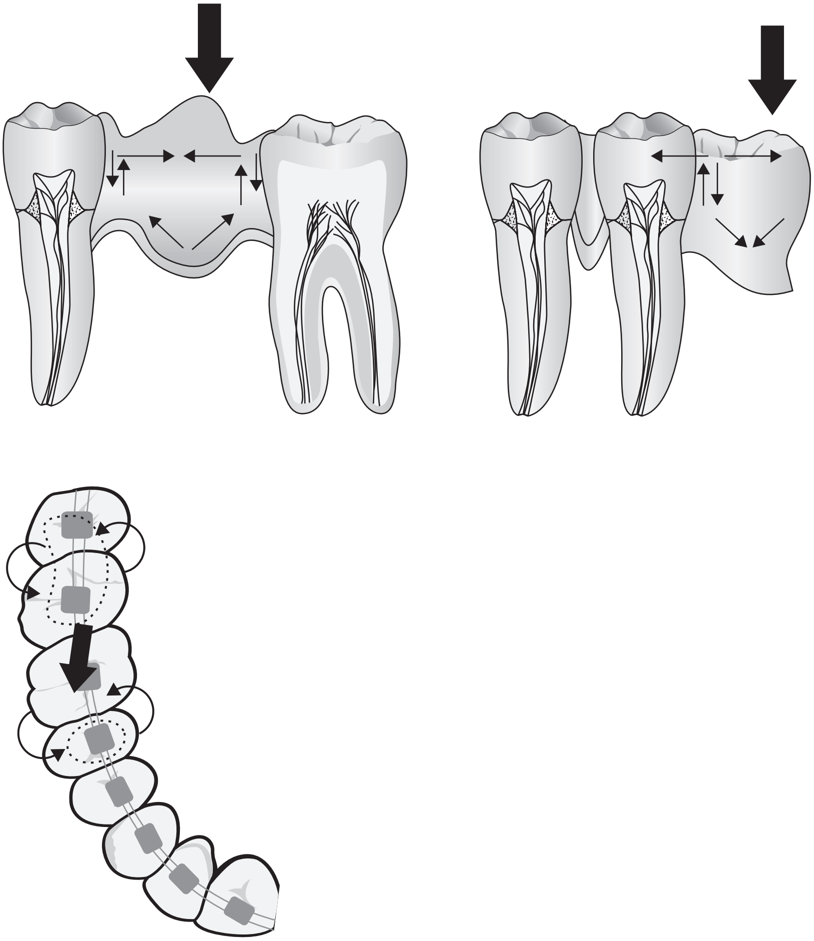

Figure 1.3 Location of tensile, compression, and shear stress vary in dental constructions. The drawing demonstrates the difference between two-end supported fixed dental prostheses (three-unit bridge) and one-end supported fixed dental prostheses (cantilever bridge) in buccal view. Occlusal view demonstrates torsional (tilting) forces when a three-unit prostheses is loaded to the buccal cusp.

cracking and fracturing than resin-based materials. Resin-based materials differ also by their toughness. Highly cross-linked and well-polymerized resins are more brittle, i.e., their toughness is less than that of cross-linked polymers with somewhat lower cross-link density and a lower degree of monomer conversion, or linear polymers where there are no covalent bonds between the polymer backbones.

Toughness is an important property for dental material. Toughness is defined as the energy required to propagate the crack through the material until it fractures. Toughness describes the damage tolerance of the restoration and tooth system. Generally speaking, a tough material is also a strong material. By selecting fillers of high aspect ratio, i.e., fibers to the resin material, even a highly cross-linked and well-polymerized polymer can demonstrate high toughness (Garoushi et al., 2013; Lohbauer et al., 2013; Bijelic-Donovan et al., 2016).

1.3 Requirements for Minimally Invasive and Adhesive Restorations

When FRC restoration is made and adhesively cemented to the remaining parts of teeth, the function of the device is based on the properties of the material components used in the restoration, their volumetric and thickness ratios and location in the construction, as well as interfacial adhesion between the material components and tooth substance. Without adequate interfacial adhesion, the occlusal loads are not carried by the restoration and transferred to the remaining teeth, periodontium, and jawbones. Failures at the material interfaces are typically shear and tensile in type, and elimination of shear and tensile stress, by turning them instead into compression stresses through the structural design of retaining elements, lowers the risk of debonding the restoration. Thus, the design principles for the FRC restorations of fixed dental prostheses, root canals retained devices or inlays/onlays and crowns, should take into consideration the type and direction of the potential damaging stress. The designing principles are demonstrated in Part 2 of this book. In addition, occlusal aspects with regard to the load distribution have to be considered when FRC restoration is constructed. Properly balanced occlusion, free of articulation interferences, enables an even occlusal stress distribution between remaining teeth and the restoration. Also, attention needs to be taken not to over-dimension the bucco-lingual/palatal width of the occlusal surfaces of the restorations, especially for pontics.

1.4 Summary: Key Requirements for FRC Materials

Key requirements for FRC materials and restorations are:

- Chemical and mechanical resistance against oral environment
- Low microbial adsorption to the material
- Correctly located material phases in the restoration
- Good interfacial adhesion between material phase
- Structural designs which lower magnitude of stress in the device and tooth system
- Properly balanced occlusion to eliminate high-localized stresses in the restoration.

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Types of FRCs used in dentistry

2

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Chapter Outline

2.1 Introduction: What are FRCs?

Fiber-reinforced composite (FRC) is a synthetic material combination of a polymeric (resinous) matrix and reinforcing fillers of high aspect ratio, i.e., the ratio between the diameter and length of the filler (Murphy, 1998). High aspect ratio fillers are fibers. Fig. 2.1 describes a typical cross-sectional and longitudinal view of continuous unidirectional FRC (Fig. 2.1). In general, a fiber is a rope or string used as a supporting/reinforcing component of composite materials. Fibers can be also as oriented fiber fabrics (a weave) of random fibers (a mat, a veil) into sheets (in plane) to make composite types of products such as felt or paper. Fibers can also be three-dimensionally oriented. The strongest engineering materials are generally made of continuous unidirectional fibers.

Fibers of the composite are the reinforcing phases when a load is applied to the composite. The load is transferred to be carried by the stronger fibers through the interface between the fiber and polymer matrix. The reinforcing fibers can be continuous unidirectional (rovings and yarns), continuous bidirectional (weaves and fabrics), continuous random oriented (mat) or discontinuous (short and chopped) random or oriented fibers. It is noteworthy that natural fibers (from plants and animals), such as cotton, flax, sisal, alpaca wool angora wool, camel hair, etc. are not feasible in medical and dental applications.

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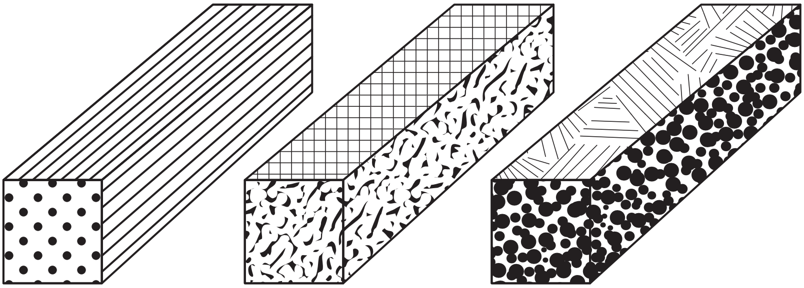

Figure 2.1 Schematic drawing of oriented continuous unidirectional FRC (on the left), plane oriented bidirectional weave (in the middle) and plane random fibers (on the left).

Of the many types of fibers available (various glass, carbon/graphite (G/F), polyethylene, and aramid) clinically the most durable and suitable have proved to be E-glass fibers (E = electric) which can be silanized and adhered to the resin matrix of the FRC (Rosen, 1978; Vallittu, 1993; Matinlinna et al., 2007; Lung and Matinlinna, 2012). The other mentioned fibers cannot be silanized due to their chemical inertness. Glass fibers vary according to their composition and most the commonly used fibers are E-glass and S-glass, which are chemically stable and durable in the pH range of 4—11, suggesting their good stability also in the oral environment (Norström et al., 2001). The basis of glass fillers and glass fibers is silica (silicon dioxide), SiO_2, which in its pure form is an inorganic polymer, $(SiO_2)_n$. Interestingly, silica has no true melting point but softens at 2000°C, where it also starts to degrade. E-glass composition is alumina-borosilicate with less that 1 wt% alkali oxides (see more below).

Other fibers attempted are, e.g., G/F fibers, but their black color has been considered as a limiting factor for their clinical use (Schreiber, 1971). Attempts to use ultrahigh molecular weight polyethylene fibers (UHMWP) have also been made (Ladizesky, 1990; Ladizesky et al., 1994), but there are problems in bonding the fibers to the resin matrix because UHMWP fibers are chemically too inert. In addition, bacterial accumulation to the UHMWP reinforced composite limits the use of fibers clinically (Takagi et al., 1996; Vallittu, 1997a, Tanner et al., 2000). Strength and rigidity of the dental construction made from FRC are dependent on the polymer matrix of the FRC and the type of fiber reinforcement (Vallittu, 2013). Table 2.1 lists the basic synthetic fiber types that have been used in dental applications.

The type and composition of reinforcing fiber and some properties of fibers influence the strength of the FRC (Table 2.2). Basic requirements are in the physical properties, especially strength and elongation percentage at break of reinforcing fiber versus the polymer matrix. Fiber reinforcement has higher strength than the polymer matrix and it elongates less than the matrix. In order to adhere the fibers to the polymer matrix, there has to be proper wetting (impregnation) of all of the fibers with the resin system. This means that the surface free energy of such fibers needs to be high. Next, the quantity of fibers in the FRC and their fiber alignment (orientation) affects the outcome FRC properties. The number of individual fibers in the FRC can be increased by selecting fibers with a small diameter. There are

Table 2.1 **Synthetic fiber types of FRC and their applications in dentistry**

Type of fiber	Application in dentistry
Glass fibers prostheses	Permanent (veneered) fixed dental Temporary fixed dental prostheses Reinforcement of removable devices Periodontal splints Orthodontic retainers Root canal posts (prefabricated, individual) Filling resin composites Repairs of conventional restorations Oral and maxillofacial surgery
Carbon/graphite fibers	Root canal posts (prefabricated)
Polyethylene fibers	Temporary periodontal splinting Temporary fixed dental prostheses Root canal posts (individual)
Aramid fibers	Temporary periodontal splinting Temporary fixed dental prostheses

Table 2.2 **Factors, which contribute physical properties of dental FRC material**

Tensile strength and elongation of fiber and polymer matrix
Impregnation of fibers with resin
Adhesion of fibers to the polymer (resin) matrix
Surface treatment and type of fibers
Orientation of fibers
Length of fibers
Volume fraction of fibers
Number of fibers and diameter of fibers in the FRC and entire restoration
Location of FRC in the restoration

reports showing that fibers with a diameter on a nanometer (10^{-9} m) scale provide a better reinforcing effect than fibers on a micrometer (10^{-6} m) scale. Typically used fiber diameters are 6–18 μm in diameter, and there no nanometer scale fibers in general use at the moment. All these aspects which influence the strength of the FRC are important especially in the fabrication of dental and FRC devices, which are of small size: there is no room for poor quality FRC material. In some other technical applications the material quality requirements can be lower, due to the larger size of the device and bigger volume of the FRC material. A special feature of dental FRC restorations is in the multiphasic structure of the device, which means that there is typically a FRC framework, which is covered with a layer of resin or resin composite, and the device is luted adhesively on tooth. Because the resin or resin composite coverage (veneer) can be relatively thick, the position of

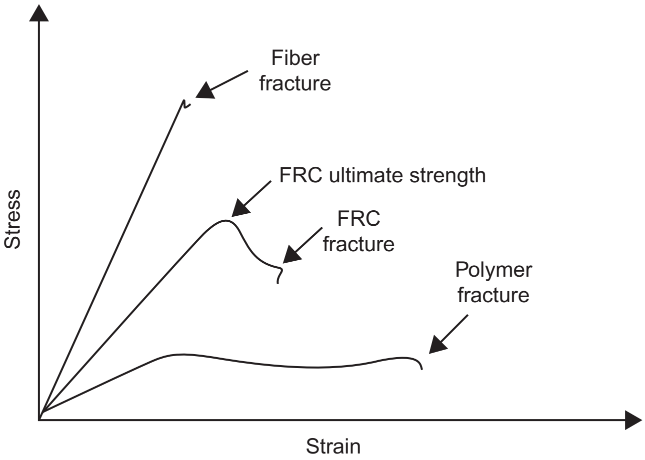

Figure 2.2 The mechanical properties of FRC are related to the properties of fibers and matrix. This figure shows stress-strain curves for fibers, matrix and composite (FRC).

the FRC framework affects the durability, i.e., fracture propagation pathway of the multiphasic dental construction.

Combination of fibers and polymer matrices provide reinforced composites, which have physical properties between the most durable phase (fiber) and weakest phase (i.e., polymer) (Fig. 2.2) (Murphy, 1998). The strength and modulus of elasticity are dependent on the volume fraction of fibers and the orientation of fibers (Fig. 2.3).

Prediction of the influence of fiber orientation to the strength of the FRC can be made by the Krenchel's factor, which with the known direction of the load gives an estimation of the reinforcing efficiency of fibers. Continuous unidirectional fibers give the highest reinforcing effect but only anisotropically in the direction of fibers (Fig. 2.4). Randomly oriented discontinuous fibers give the reinforcing effect three-dimensionally, i.e., isotropically.

The process used to introduce the fibers together with the resin, i.e., impregnation of fibers with resins, should preferably be done by the producer of the fiber product. Impregnation of the fibers with dental resin systems at the dentist's office or in the dental laboratory is a tedious, demanding, and time consuming stage in the production of FRC devices and can lead to FRC material with internal voids (pores and gaps).

The degree of impregnation of glass fibers (rovings, weaves) is influenced by the surface chemistry of fibers, which is modified by surface sizing with silanation and viscosity of the resin system. It is known that fibers are difficult to impregnate with resin systems of high viscosity (Vallittu, 1995). Such high viscous resin systems are especially those mixed from a polymer powder, such as poly(methyl methacrylate) (PMMA) and a monomer liquid (methyl methacrylate (MMA), which are used in denture bases, provisional FPDs, and removable orthodontic appliances. Light curing resins with particulate fillers are also highly viscous resin systems. The complete impregnation of silanized glass fibers by the resin allows the resin to

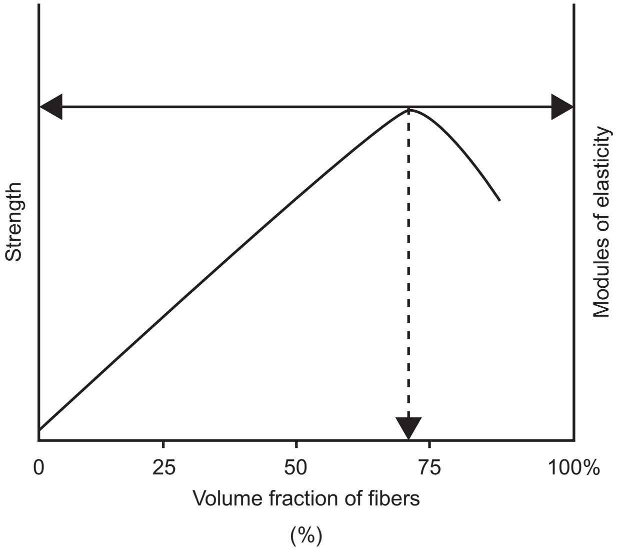

Figure 2.3 The relationship between the volume fraction of fibers in the polymer matrix of FRC and ultimate strength follows the law of mixtures. Maximum loading of continuous fibers is c70 vol%, which still enables proper impregnation of fibers by the resin with regular fiber diameters.

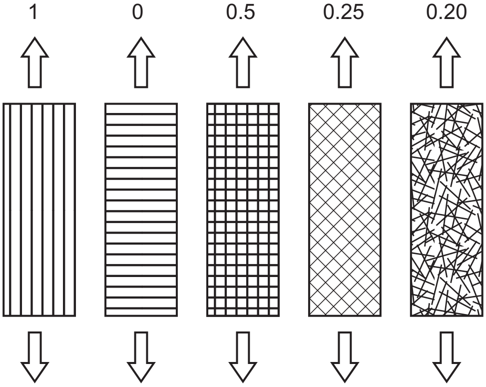

Figure 2.4 Reinforcing effect of fibers with different fiber orientation. Arrows show the direction of force and the number refers to the reinforcing efficiency by the fibers (the Krenchel's factor).

come into contact with every fiber. If complete impregnation is not reached due to high viscosity or polymerization shrinkage of the resin, the mechanical properties of FRC do not reach the optimal values, which could be calculated by laws of mixture. Aspects which relate to the resin impregnation are discussed in another chapter of this book.

2.2 Mechanical Properties of Continuous FRC

Mechanical strength of FRC materials is most often described by the value obtained from the three-point flexural strength (bending strength) test. In bending, the homogeneity and location of the fiber-rich layer of the specimen influences considerably the strength values. This means that if specimens with the same geometry and dimensions have variation in their fiber location, the strength of the specimen varies as well. The fibers have the highest reinforcing effect when they are located at the side of highest tensile stress in the specimen (Fig. 2.5). The tensile stress is transmitted to the fibers and the highest reinforcing efficiency (the Krenchel's factor = 1) can be achieved with the fibers closest to the surface of the highest tensile stress. In the neural axis, there is practically speaking no reinforcing effect by the fibers. If the fibers are only on the compression side, the specimen fails by fiber buckling. Cross-sectional view of the material with correctly located low volume fraction of fibers and provides almost equal strength and toughness as the specimen with high volume fraction of fibers (Dyer et al., 2005) (Fig. 2.6).

Failure types of continuous FRC and discontinuous FRC vary from each other, the latter being related to the fiber length. As described above, the continuous unidirectional FRCs have the highest strength in the direction of fibers (the Krenchel's factor = 1). Continuous unidirectional FRCs can exhibit four types of failure according to type of the stress applied to the material. Under tensile stress in the direction of load, the FRC fails by axial tensile failure where the polymer matrix and fibers are fractured (Fig. 2.7). The fracture surface typically shows protrusion of fibers to some extent. Protrusion of fibers is affected by the interfacial adhesion between fibers and polymer matrix. The effect of interfacial adhesion can be demonstrated e.g., by

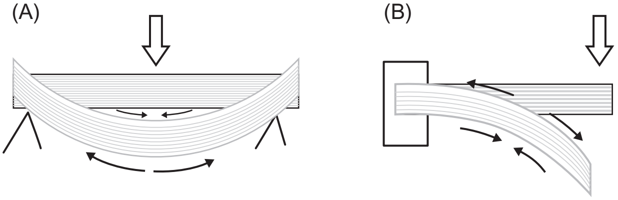

Figure 2.5 Schematic illustration of (A) three-point bending test, where the most effective fiber reinforcement is located at the tension side of the specimen rather than in the neutral axis of at the compression side, and (B) two-point bending test (cantilever) where the tension side is the upper side.

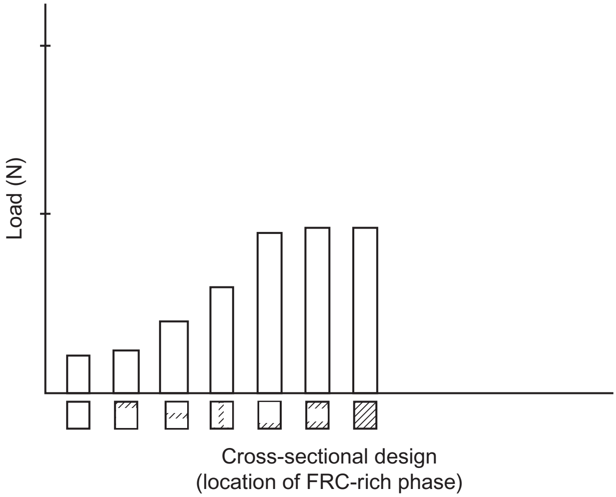

Figure 2.6 Schematic illustration of ultimate flexural strength of FRC specimens with the same dimension but different fiber volume loading and fiber location (geometry) in the cross-sectional view (Dyer et al., 2005).

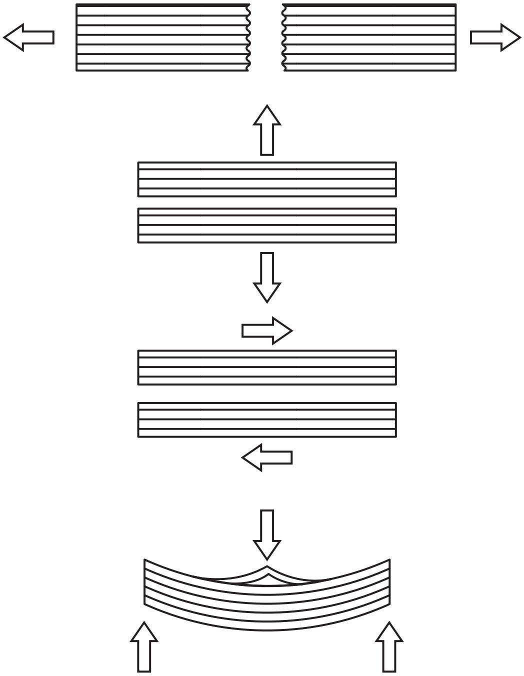

Figure 2.7 Failure types of FRC material: from top to bottom: axial tensile failure, transverse tensile failure, shear failure, and buckling failure.

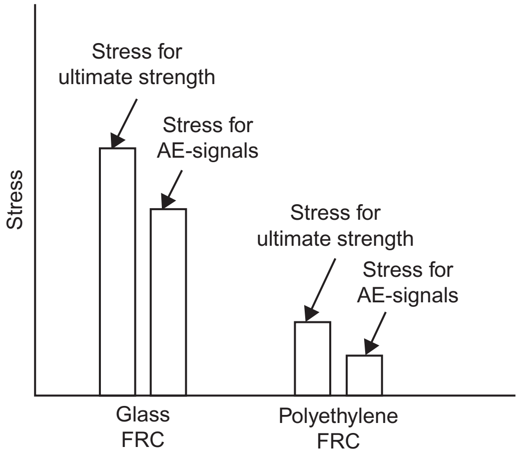

Figure 2.8 A histogram showing the ultimate flexural strength of glass and polyethylene FRC and the level of stress for the first acoustic signals from the material. Magnitude of acoustic emission signals demonstrates that the first interfacial cracks between the fibers and matrix has occurred (Alander et al., 2004).

determining acoustic emission (AE) signals from the material during a loading event. Shear stresses at the fiber-polymer matrix interface emit AE signals when the interfacial failure is occurring. AE analysis can be used to determine resistance of the fiber-polymer matrix interface to debonding shear stress (Fig. 2.8).

In the perpendicular direction of the fibers, the FRC fails by transverse tensile failure, and if the FRC is affected by shear stress, the failure type is called shear failure. In bending, the stress type varies from tensile to compression and shear according the dimensions of the FRC specimen and the span length. The fourth type of failure is the buckling of fibers, which occurs on the surface of the specimen under compression stress.

The static strength (ultimate flexural strength) of the FRC is dependent on the fiber quantity to the level of approximately 68 vol%. A high quality glass FRC material with high fiber quantity provides high flexural properties (with E-glass *ad* 1250 MPa) (Lassila et al., 2004). Water sorption of the polymer matrix reduces the strength and modulus of elasticity of the FRC of semi-IPN polymer matrix by approximately 15% within a 30 days water storage time at 37°C (Fig. 2.9). Reduction of strength is predominantly due to plasticization of the polymer matrix by diffusion of water molecules to the polymer structure. A positive correlation exists between water sorption of polymer matrix and the reduction of flexural properties (Lassila et al., 2002; Bouillaguet et al., 2006). For instance, high water sorption of polyamide (nylon) matrix containing FRC causes reduction of over 50% in strength of FRC. The reduction of the flexural properties is reversible, i.e., dehydration of the FRC recovers the mechanical properties. No significant reduction of flexural strength and modulus even in long-term water storage (*ad* 10 years) occurred.

Testing conditions have a considerable effect to the strength and modulus of elasticity values, which are calculated with commonly used mathematical formulas

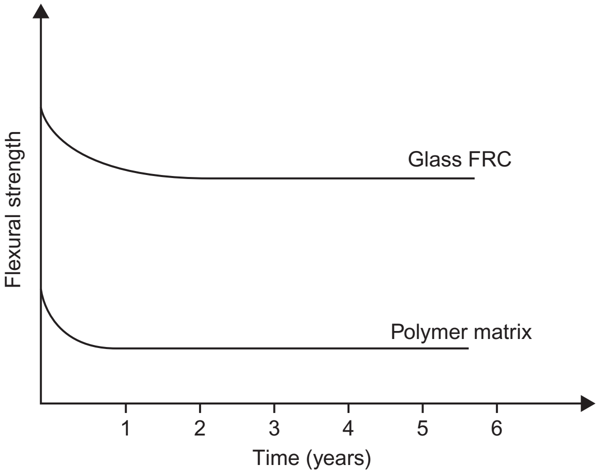

Figure 2.9 Long-term water storage reduces flexural strength and modulus of elasticity mostly during the first 30 days due to water absorption and related plasticization of the matrix.

based on the width, height, and span length of the specimen and the force required to break the specimen (Alander et al., 2005). Results are given in MPa (N/mm^2) and the calculations take into consideration the variation in the specimens' dimensions and span length. However, stress distribution in the specimens may contain also a considerable component of shear stress and therefore the values in MPa are not necessarily absolute values for the strength. They have to be interpreted with the knowledge of the dimensions and span length of the test design. With a constant span length, thinner specimens reveal higher flexural strength and modulus of elasticity values than obtained with specimens of the same material but larger dimension. Thus, the strength values of specimens of exactly the same diameter and span length in test set-up are comparable. This is of high importance in the interpretation of results obtained e.g., from root canal posts and in comparison of FRC materials of different brands.

2.3 Reinforcing Effect of Discontinuous Fibers

Long continuous fibers, which have been used as an example of FRC in this book thus far, are FRCs with highest anisotropic mechanical properties. This is because of the large surface area of fibers, which enables bonding of fibers to the polymer matrix to occur on a larger surface area than if discontinuous short fibers are used. Depending on the fiber length, discontinuous short fibers have reinforcing efficiency between long continuous fibers and particulate fillers of low aspect ratio. The critical fiber length (l_c) is a parameter of the minimum length at which the center of the fiber reaches the ultimate strength, when the matrix achieves the

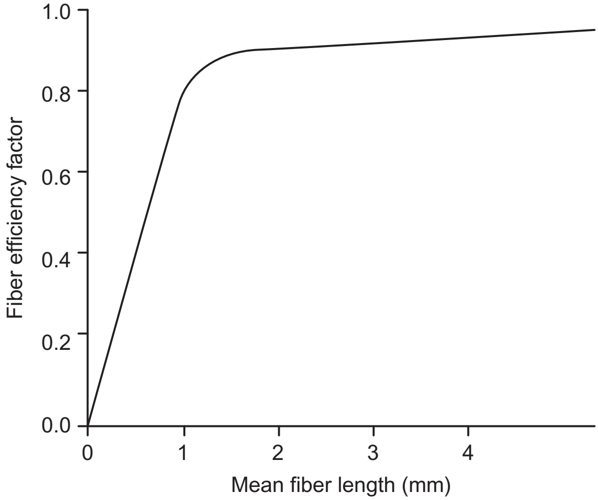

Figure 2.10 Example of the relationship between fiber length (mm) and reinforcing efficiency (Kardos, 1993, Vallittu, 2014).

maximum shear strength (Kardos, 1993). The critical fiber length can be determined e.g., by single fiber fragmentation test, where length of fiber fragments in the polymer matrix can be used to determine the critical fiber length. The critical fiber length is related to the elongation at break of the polymer matrix and fibers, and to a large extent to the adhesion of fibers to the polymer matrix (Vallittu, 2014). An example of the influence of the length of fibers to the reinforcing efficiency is shown in Fig. 2.10.

Consequently, the behavior of FRC under load is different when the continuous fibers are cut (to be discontinuous fibers) for instance to be used in applications where there is no space for long fibers, like in fillings and core-build-ups of tooth. Discontinuous short FRC has properties which relate to the direction of fibers but also to the length of fibers (Batdorf, 1994; Garoushi et al., 2012). By changing continuous unidirectional fibers to longitudinally oriented discontinuous fibers of lower aspect ratio, ultimate tensile strength of the FRC is lowered (Fig. 2.11). In this case both FRCs represent anisotropic composites. When the fiber direction is changed to random, the strength is reduced even more and the FRC becomes isotropic. The effect of the aspect ratio (length/diameter of fibers) is related to the "critical fiber length," which can be defined as the minimum length of fiber that still has a reinforcing effect. Interfacial fracture energy of the adhesive interface between the fibers and polymer matrix versus the tensile strength of the fiber has an impact on the critical fiber length. It has been concluded that the critical fiber length could be as much as 50 times the diameter of the fiber. The diameter of glass fibers currently used in dental FRCs is 15−18 μm and the critical fiber length should be, therefore, between 0.75−0.9 μm (Vallittu, 2014). Orientation of discontinuous fibers can be random three-dimensionally or two-dimensionally (in plane). Packing of discontinuous FRC to the tooth cavity orientates the longest discontinuous fibers

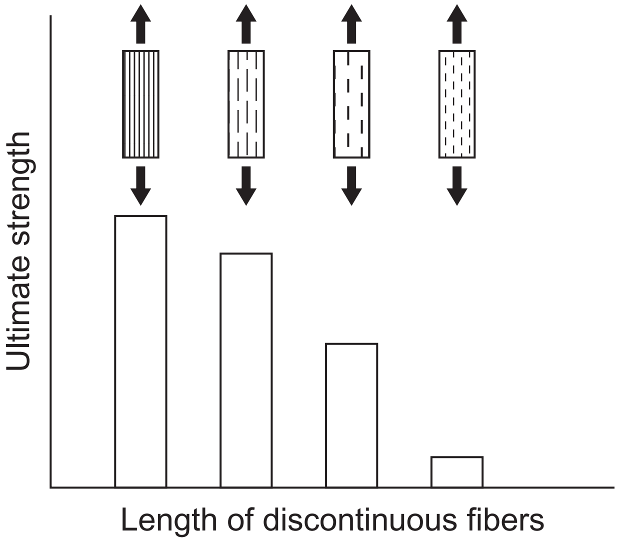

Figure 2.11 Effect of the length of oriented fibers on the ultimate strength of FRC. Fibers that are shorter than the critical fiber length (l_c) behave like particulate fillers and do not effectively reinforce the composite.

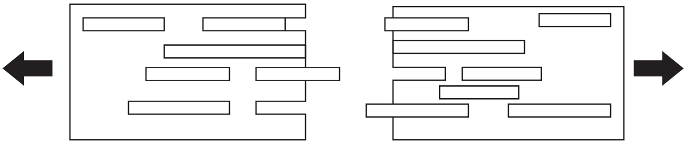

Figure 2.12 Failure types of discontinuous FRC including cracking of the polymer matrix, debonding of the fibers, and fracture of the fibers.

two-dimensionally, which places their fiber ends to be perpendicular to the axial walls of the tooth cavity. Packing and newly oriented fibers improves mechanical interlocking of the FRC to the cavity walls and also decrease curing shrinkage at the interface of FRC and cavity walls. Failure types of discontinuous FRC including cracking of the polymer matrix, debonding of the fibers, and fracture of the fibers, is shown in Fig. 2.12. Utilization and function of discontinuous fibers in clinical applications is presented in Part II of this book.

2.4 Glasses Used in Reinforcing Fibers

Most of the today's reinforcing synthetic fibers in dentistry are glass fibers due their transparency and beneficial surface chemistry, which allows their adhesion to resin

Table 2.3 **Nominal composition (%) of certain glass fibers (Cheremisinoff, 1990; Vallittu, 2014)**

Component	Type of glass			
	E	**A**	**R**	**S**
SiO_2	53–55	70–72	60	62–65
Al_2O_3	14–16	0–2.5	25	20–25
CaO	20–24	5–9	6–9	–
MgO	20–24	1–4	6–9	10–15
B_2O_3	6–9	0.5	–	0–1.2
K_2O	<1	1.0	0.1	–
Na_2O	<1	12–15	0.4	0–1.1
Fe_2O_3	<1	0–1.5	0.3	0.2

matrix via silane coupling agents (silanes) (Matinlinna et al., 2004; Lung and Matinlinna, 2012). Use of other reinforcing fibers like G/F or aramid causes severe cosmetic problems for the restoration. Other benefits of glass fibers in reinforcing acrylic polymers of a brittle nature include low elongation at break and high tensile strength. Glass types of E-glass and S-glass and their behavior as component of dental FRC are recently reviewed in more detail in another source (Vallittu, 2014a). S-glass is divided to subclasses (S2, S3 etc.) based on the surface sizing of the fibers.

It is known that the chemical composition of glass plays an important role in the manufacturing of fibers and in the chemical stability of fibers against effects of water and acids. It has been shown that the chemical resistance of glasses toward glass deterioration relates to the composition, the state of the glass surface, the amount and type of attacking solvent media, temperature, and time. In the presence of water, the strength of the fiber may be reduced, especially with glass fibers of high alkali metal oxide content (Vallittu, 1998a). There are so-called A-, C-, D-, E-, E-CR-, R-, and S-glasses, and the most suitable for use in dental and medical applications are alkali-free glasses E-, R-, and S-glasses (Table 2.3).

Certain glass forming agents, including boron oxide (B_2O_3), are leached from the surface of glass fibers, and thereby the supporting glass network can be splat at different places. The process of production of glass fibers may contain elimination of easy leaching oxides from the surface of fibers by acid washing process, which can increase the stability of fibers later on. The chemical composition of glass fibers is different on the fiber surface than in the inner part of the fiber. The surface of E-glass may be enriched with boron and calcium. The glass composition has a considerable effect of resistance of the fibers against the influence of acids and, e.g., E-glass has good resistance in a wide pH range (Nordström et al., 2001) (Fig. 2.13).

Continuous and discontinuous glass fibers in dental FRC products are usually made of alkali-free glass (less than 1% $Na_2O + K_2O$), known as E-glass (Cheremisinoff,1990). Because of the high calcium oxide content, glass similar to this composition shows poor resistance to acidic solutions. For this reason, the

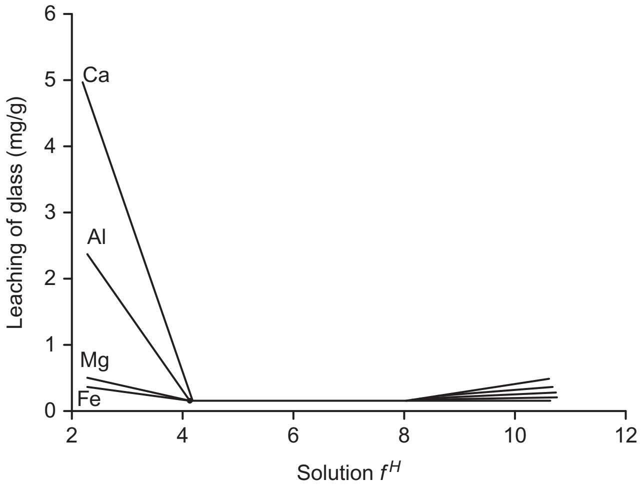

Figure 2.13 Resistance of E-glass against dissolution at various pH (Nordström et al., 2001).

Table 2.4 Some physical properties of glass fibers (Cheremisinoff, 1990; Vallittu, 2014)

Property	**Type of glass**			
	E	**A**	**R**	**S**
Density (g/cm^3)	2.54–2.59	2.48	2.50	2.49
Tensile strength (10^{-2} N/mm^2)	25–34	24–31	44–48	49
Young's modulus (10^{-3} N/mm^2)	73–77	70–7	86	86

composition of E-glass is modified by introducing boron oxide (B_2O_3) and by decreasing the CaO content. The other type of glass used in dental FRCs is S-glass, which provides slightly higher tensile strength than E-glass. Radiopacity (X-ray opacity) of glass fibers is related to their elemental composition and therefore dental applications may utilize glasses which have been tailored for dental use. Another possibility to enhance radiopacity of FRC is to include radiopaque fillers (i.e., fillers containing some heavy metal ions) to the polymer matrix. However, fillers require space, and therefore volume loading of fibers is reduced, which lowers the strength of the FRC. Table 2.4 lists some physical properties of glass fibers.

2.5 Resins Used in FRC

Synthetic polymers used in FRCs can be distinguished, for instance, by their polymer chain structure. Once the polymer has been polymerized by a setting reaction of monomers, the polymer structure can be either linear or cross-linked (Cogswell, 1991). A linear polymer, called also a thermoplastic polymer is formed when the monomer unit has only one reactive functional vinyl group; in the case of dental resins systems – mostly methacrylate group (Ruyter, 1982). After initiation of the free radical addition polymerization (vinyl polymerization), the linear polymer chains are not bound covalently with each other. Bonding of polymer chains is occurring by relatively weak cohesive forces of van der Waals (also known as London forces). Typical monomers, which convert in polymerization to linear polymer structure, are MMA (methyl methacrylate). MMA is typically used as the major monomer component of denture base polymers, where the polymerization initiation system is based on temperature sensitive compound (benzoylperoxide) or an additional activator of tertiary amines (heat-cured or auto-polymerized denture base resins, respectively) (Ruyter and Öysaed, 1982). Acrylic polymers have a vast amount of other applications in dentistry, such as denture repair materials, soft liners, impression trays, provisional restorations, resin composite cements, filling materials, and oral and maxillo-facial appliances. Denture base polymers are multiphase polymer systems where the monomer of MMA is mixed with prepolymerized powder beads of PMMA. Interestingly, the acrylic polymer PMMA was introduced to the market as a denture base material in 1937. Before then, other synthetic (and less convenient) materials, such as nitrocellulose, phenol formaldehyde, and vulcanite were used for denture bases.

There is also a minor proportion of cross-linking monomer system included, typically ethyleneglycol dimethacrylate (EGDMA), which improves mechanical properties of the polymer. A mixture of PMMA beads and monomer system of MMA-EGDMA is highly viscous, especially heat-cured resin. This obviously puts demands for the proper wetting and impregnation of fiber systems (Vallittu, 1998b).

If there are two or more reactive groups – methacrylate groups in this case – in the monomers, there are also two reaction sites for free radical polymerization to occur. Dimethacrylate monomers are examples of monomers of this kind, and polymerization results in a covalently bound cross-linked polymer structure. A cross-linked polymer is also called a thermoset polymer. Polymerization by blue light initiation ends up to the certain degree of monomer conversion, i.e., saturation of carbon-carbon double bonds of the methacrylate groups (c.55%–65%) and formation of covalent bonds between the monomers. That said, a large portion of methacrylate groups remain unsaturated inside the polymer structure and there are also a few completely unreacted monomers in the structure, called residual monomers. Fig. 2.14 illustrates the structure of linear and cross-linked polymers.

In general, in engineering applications, the resin systems in thermosetting FRCs are based on polyesters, vinyl esters, epoxides, phenols, and furanes which have different chemical resistance toward the effects of acids and alkaline solutions, and aliphatic and aromatic solvents. Resistance can be tested by immersing the polymer in media for a certain period of time and following the changes in the physical properties. In thermoset resins, the cross-links between the polymer backbones are covalent in nature and here the dissolving of the resin matrix by solvents does not occur. The media can, however, cause swelling of the resin matrix and cause reversible changes in the physical properties. Swelling increases mobility of the polymer chains (polymer backbones), which plasticizes the matrix, and lowers the modulus

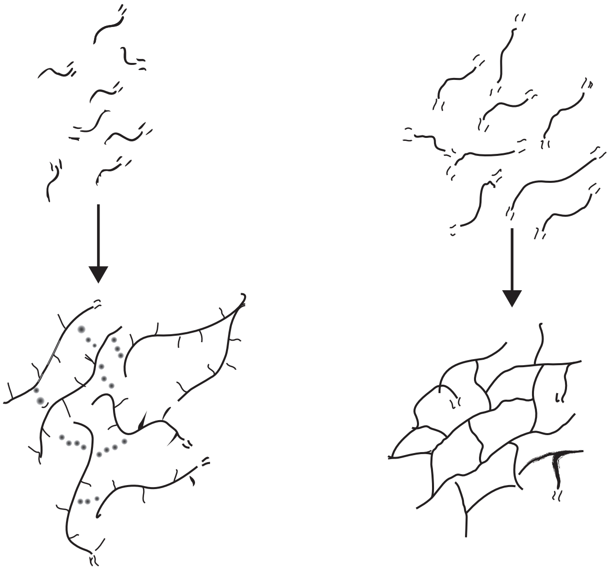

Figure 2.14 Monofunctional monomer systems (e.g., MMA) produced linear polymer (on the left) whereas bifunctional monomers (e.g., *bis*-GMA) produce cross-linked polymer (on the right).

of elasticity and surface hardness. Transport of the media into the matrix is influenced by diffusion, which depends principally on the structure of the resin, the temperature, type, and viscosity of the media.

Of all synthetic polymers, acrylic polyester resins are the most widely used. The weak point of polyesters is the ester group, which can be deteriorated by hydrolysis, i.e., reaction with water. However, with the introduction of an aromatic ring in the resin chain, the resistance against water increases considerably. Given this, polymers that are polymerized from monomer systems based on bisphenol derivatives show good resistance towards the effects of water and alkaline solutions. This is an important aspect, which relates to the FRCs used in dentistry and surgery, because bisphenol-A-glycidyl dimethacrylate (*bis*-GMA) based resin systems are widely used. Another commonly used resin system is epoxy resins, which also demonstrate good chemical resistance. Epoxy resins have been successfully used e.g., in the polymer matrix of FRC root canal posts.

Dental FRCs utilize resin systems, which are based on bis-GMA, triethyleneglycol dimethacrylate (TEGDMA), and urethane dimethacrylate systems (UDMA). All of these can produce cross-linked thermoset polymer matrices for the FRC. In order to increase toughness of the matrix, surface adhesive properties, and clinical handling properties before curing, amounts of linear polymer of PMMA have been added to the matrix. A mixture of cross-linked polymer and linear polymer is the so-called semi interpenetrating polymer network (semi-IPN) (Sperling, 1994; Vallittu, 2009). Currently, the IPNs are used in denture base polymers, denture teeth, FRCs, and very recently, in restorative resin composites. Both types of resin systems and polymers, namely cross-linked (thermoset) and linear (thermoplastic)

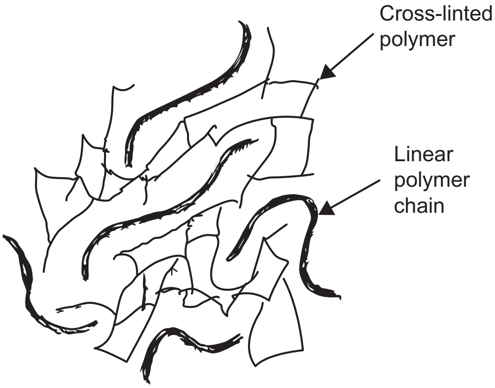

Figure 2.15 Polymer structure of interpenetrating polymer network (IPN) systems where there are linear polymer chains in the structure of cross-linked polymer.

polymers can be used in dental FRCs. Technically, and in terms of using the FRC, the type of the resin system plays a significant role.

The IPN resin systems are based on using combination of thermoset and thermoplastic types of resins. The typical IPN system is a semi-IPN having the cross-linked polymer and the linear polymer mixed together (Sperling, 1994) (Fig. 2.15). The dental IPNs are predominantly semi-IPNs in which one or more polymers are cross-linked and one or more polymers are linear or branched. Dimethacrylate monomers or multifunctional monomers and dendrimers typically form the cross-linked part of the semi-IPN, and PMMA is forming the linear part of the semi-IPN system. The IUPAC Commission on Macromolecular Nomenclature based name for the semi-IPN made of bis-GMA, TEGDMA, and PMMA is *net*-poly(methyl methacrylate)-*inter-net*-copoly(bis-glysidyl-A-dimethacrylate)-triethyleneglycol dimethacrylate.

In polymerization the dimethacrylate monomers form a predominantly cross-linked semi-IPN structure with phases of the linear polymer PMMA. Cross-linked polymer matrix forms FRC with higher modulus of elasticity than that obtained by thermoplastic or semi-IPN polymers (Pastila et al., 2007). On the other hand, thermoplastic and semi-IPN polymer matrices provide higher toughness than FRCs made of highly cross-linked thermosets. Semi-IPN polymer matrix of FRC provides benefits over cross-linked dimethacrylate or epoxy types of polymer matrices in handling properties and bonding of indirectly made restorations and root canal posts to resin luting cements and veneering composites (Mannocci et al., 2005; Frese et al., 2014; Wolf et al., 2012).

2.6 Impregnation of Fibers With Resin

Good contact of reinforcing fibers to the resin matrix is an essential requirement for adhesion of fibers with the resin. Wetting of the surface of the fiber is required in the first instance and when there are more fibers, like in the fiber roving, yarn, or weave. The term describing the penetration of resin material to the spaces between the fibers is called resin impregnation. Resin impregnation relates to the surface wetting properties of fibers by the resin, distance of individual fibers from each other in the fiber product, and viscosity of the resin material (Ekstrand et al., 1986; Vallittu, 1998b). Tightly bound fiber weaves and ribbons are more challenging to wet with the resins (Vallittu, 1997a).

Out of the several types of resin system which are used in dentistry, the most demanding resins for impregnation purposes are the powder-liquid type denture base polymers. Denture base polymers are composed of PMMA powder beads, which do not completely dissolve by the MMA monomer liquid used, before the monomer is cured. Due to large PMMA powder particle size (30−60 μm), the space required for the resin between the fibers is the same or larger than the powder bead size. If impregnation of the fibers can be achieved, the distance from one fiber to the other fiber is great, which reduces the number of fibers, and thereby the fiber volume in the composite. In principle, the fibers could be impregnated with the plain MMA monomer liquid only, but this has been shown to cause internal polymerization contraction voids between the fibers, which being filled with air can even predispose to internal oxygen inhibition of the polymerization of MMA (Vallittu, 1997b). The polymerization shrinkage of MMA is 21% in volume and the polymerization shrinkage of MMA can also cause dimensional changes in the FRC (Vallittu, 1996).

To overcome the problem of impregnation of the fibers with the highly viscous denture base acrylic systems, a specific preimpregnation method was developed (Stick Classic, Stick Tech-GC Group). In the preimpregnation method, PMMA of molecular weight (M_w) of 220,000 is dissolved in a highly evaporative solvent and the fibers are impregnated with the PMMA-solvent solution (Vallittu, 1999). Fast evaporation of the solvent leaves the PMMA polymer between the fibers in a porous form. When the fibers are used in denture fabrication of repair, the PMMA preimpregnated fibers are wetted with the monomer liquid only, which reacts with the porous PMMA between the fibers (Fig. 2.16). The ratio of polymer-to-monomer is in the same range as in the powder-liquid system of denture base resins, and the polymerization contraction and dimensional changes are therefore controlled.

In the impregnation of fibers with monomer systems of thermosets, namely with forming cross-linking polymers, the viscosity of the monomer systems also plays a role. Unlike in the powder-liquid acrylates, there are no powder bead fillers in the resin and the required space for the resin between fibers is less. Therefore, high fiber loading can be reached with the monomer systems of thermosets (Kolbeck et al., 2002). Tests to utilize melt thermoplastics in impregnation of fibers by pultrusion process for dental FRCs have also been made, but the system has not started to be used generally (Goldberg et al., 1994). For improving handing and bonding properties of fiber products by dental laboratory technicians and dentists, the thermoset monomers can be mixed to thermoplastic polymers (polymethylmethacrylate), which will form a semi-IPN resin matrix for the FRC material (everStick products, Stick Tech−GC Group). In the resin impregnated fibers of this kind, there is also an enrichment of PMMA on the surface layer of FRC material (Fig. 2.17).

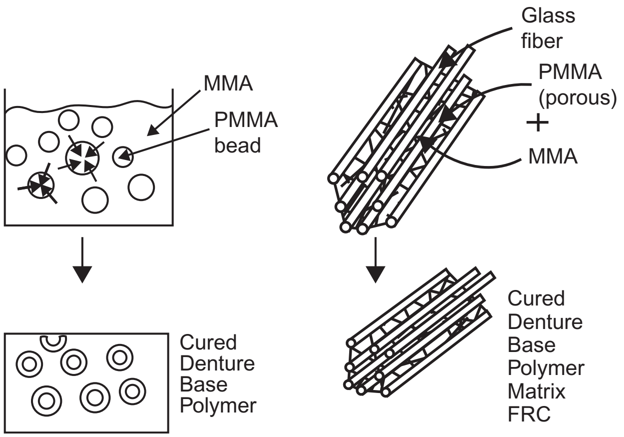

Figure 2.16 Schematic drawing of mixing denture base resin from PMMA powder and MMA liquid and analog process to impregnation of fiber prepreg which has been preimpregnated with porous PMMA, and the cured polymer, respectively.

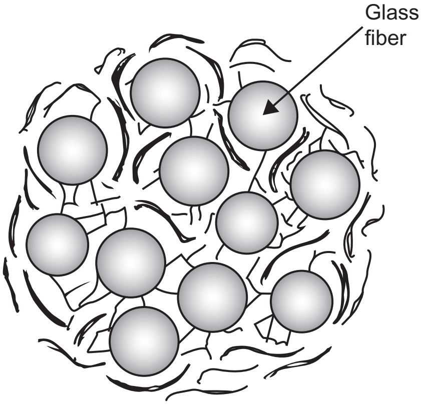

Figure 2.17 Structure of FRC system with semi-IPN polymer matrix and enrichment of linear polymer on the surface allowing better bonding properties.

2.7 Interfacial Adhesion of Fiber to Polymer Matrix

As described above, for having a load transferred in the FRC from the weaker polymer matrix to be carried by the stronger, reinforcing fibers, there is need for adequately strong adhesion of reinforcing fibers to the polymer matrix (Fig. 2.18) (Murphy, 1997). Adhesion of glass fiber, as being described also previously (Vallittu, 1995) is based on the surface chemistry of glass fibers, chemical or physicochemical treatment of the fibers, and the type of the resin system. Typically, all glass fibers contain hydroxyl groups (-OH) on their surface and they potentially

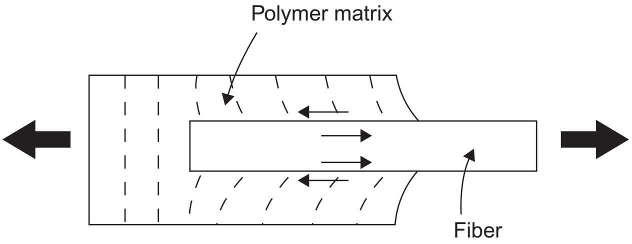

Figure 2.18 Silane promoted adhesive interface between fiber and polymer matrix transfers load when force (*F*) is applied to the fiber.
Modified from Cheremisinoff, N.P., 1990. Handbook of ceramics and composites, In: Ehrenstein, G.W., Schmiemann, A., Bledzki, A., Spaude, R. (Eds.), Chapter 9: Corrosion Phenomena in Glass-Fiber-Reinforced Thermosetting Resins. Marcel Dekker, USA, pp. 231–268.

have good adhesion to the resinous materials. These fibers are both glass and quartz fibers (Cheremisinoff, 1990).

In this case, adhesion is promoted with chemical surface treatment of fibers, called sizing and silanization (or silanation). Sizing has many functions and is a process whereby fibers are coated with antistatic compounds (that are usually diluted in water). Sizing can be a very complex blend of ingredients. Such ingredients are typically one (or several) polymeric components, a coupling agent, and a range of additives. These additives can be antistatic agents, plasticizers, rheology modifiers etc. The functions of the sizing can be related to production of the fiber, processing of the fiber, and the interfacial properties provided by the sizing between fiber surface and composite matrix. Commercial glass fibers that are used in FRCs are almost always pretreated with a silane coupling agent, known as "silanes" (Matisons, 2009). Such coupling agents are reactive with both the inorganic glass surface (and other inorganic surfaces) and with the unreacted vinylic carbon-carbon double bonds in a resin matrix. Good, preferable substrates are those containing −OH groups and/or silica (quartz, glass, alumino-silicates etc.). Silane-aided adhesion is weak for, e.g., graphite, zirconia, alumina, marble, and gypsum.

Silane coupling agents are synthetic hybrid inorganic-organic compounds containing one or more Si-C (or Si-H) bonds. They are used mainly as surface-coating agents for surface modification and as coupling agents for adhesion promotion between two dissimilar materials. Such bonds are artificially created and cannot be found in nature. Silanes have wide application in industry, but interestingly, also in dentistry and medicine. The role of silanes as either surface-coating or coupling agents depends on their actual chemical structure. A wide variety of reactive organic functional groups can be bonded to the silicon atom, such that silanes can react with the functional groups of many different substrates, like various polymer matrices (Lung and Matinlinna, 2013)

Silane coupling agents improve surface wetting of fibers and enable chemical adhesion of fibers to the polymer matrix. The silane function is based on polycondesation of hydrolyzed silanol groups to the hydroxyl groups on the surface of the

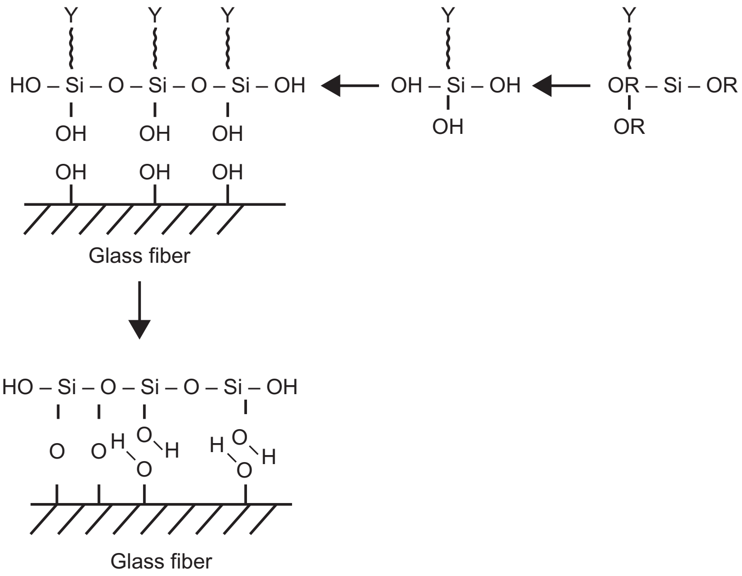

Figure 2.19 Adhesion of glass fibers to the resin matrix via silane coupling agent (chemical bonding theory): -RO groups are hydrophobic alkoxy groups that hydrolyze (catalyzed by acid) to hydrophilic Si-OH (silanols) which then condense forming chemical bonds and creating a hydrophobic siloxane film, network.
Modified from www.sibond.com, accessed 2016.

glass fiber to finally form chemical bonds (Rosen, 1978, Matinlinna et al., 2007) (Fig. 2.19). There are several methods for applying silanes onto different substrates. Functional silanes can be prepared by dissolving the silane in a solvent mixture (ethanol-water) at pH 4.0–5.0. Addition of a suitable acid is usually needed for catalyzing hydrolysis of silanes. The substrate is immersed (or dipped) in the solution and then taken out for drying. A thin layer of silane film can also be applied onto a substrate surface by brushing or by spraying, and then allowing the film to dry and cure. Another method of silane coating is by chemical vapor deposition. In a closed chamber, the silanes are heated under reduced pressure, and the silane vapor becomes deposited onto the substrate surface. Silanes can be also deposited by spin coating. In this case, the silane solution is deposited by spinning at low speed, and then the substrate is rinsed (Lung and Matinlinna, 2012, 2013).

The mechanisms of reactions of silane couplings agents are based on surface wettability and chemical bonding theories. Third suggested mechanism of action is the so-called restrained layer theory, which utilizes the elasticity of the polycondensed siloxane layer to even the stress peaks between polymer matrix and glass fiber of higher modulus of elasticity during loading conditions. Surface wettability theory and chemical bonding theory are presently the most accepted theories of function for silanes.

The role of silanes as coupling agents depends on their chemical structure. The general formula for functional silanes consists of a backbone of the type $Y-(CH_2)_n-SiR_3$. The hydrolysis of hydrophobic $-SiR_3$ ($R=$ alkoxy groups) will form oligomeric hydrophilic -SiOH (silanols), which then can bond (condense) to the surface hydroxyl groups of inorganic substrates, such as glass fibers, forming chemical bonds. However, the hydrolysis of alkoxy groups may not be complete. By varying the nature of the organofunctional functional group Y (such as methacrylate), silanes can act as surface-modifying agents and coupling agents. This said, Y can be $-NH_2$ (amino) or $>C{=}C<$, (vinylic carbon-carbon double bond) which would react with epoxy resins or vinyl and acrylate resins. These functional silanes can act as a coupling agent to connect a resinous matrix to an inorganic substrate surface. In addition, the oligomeric silanols that are formed need to retain some degree of compatibility and solubility. This is necessary for interaction with the polymer matrix. Cured silane coupling agents form finally a hydrophobic (but reactive) silane film (polysiloxane network) (Matinlinna et al., 2004; Lung and Matinlinna, 2012, 2013).

Adhesion of other types of reinforcing fibers than glass fibers to the polymer matrix is based on different mechanisms. Adhesion of G/F fibers is more physicochemical in nature and fibers of UHMWP can only be adhered after the fiber surface has been treated with high-energy plasma treatment for generating free radicals to the UHMWP surface. This requires special systems and the time-related durability of free radicals on the surface is limited. Therefore, the present UHMWP fibers cannot be used as a reinforcing component of high strength FRC and can be considered as temporary restorative materials only (Takagi et al., 1996; Vallittu, 1997a).

A good quality and well polymerized FRC undergoes hardly any significant permanent changes of properties by the influence of water in the oral environment. However, the molecular bonds at the interface of glass fiber and silane coupling agent is a potential place of attack for hydrolytic degradation (Rosen, 1978). Such degradation may occur at the polysiloxane network or at the surface of the glass fiber. The latter is influenced by the chemical composition of glass fibers and their surface treatment prior sizing and silanization. If irreversible reduction of mechanical properties of FRC exists, that is a sign of degraded interfacial adhesion between reinforcing fibers and the polymer matrix. High quality dental FRCs have good resistance against irreversible degradation of fiber-polymer matrix adhesion (Bouillaguet et al., 2006)

If the media, water or saliva, can come into contact with glass fiber by exposing the glass fibers during finishing the restoration, by cracks or microcracks in the composite, the proceeding of the saliva and water along the interface is much greater than the diffusion through the polymer matrix. This is due to the capillary effect of the glass fiber, which may exist in the FRC laminate. The inevitable shrinkage of resin by polymerization may also cause capillaries between the fibers and the polymer matrix as has been shown to happen, especially with resin systems of high polymerization shrinkage, namely monomers of MMA (Vallittu, 1994).

2.8 Summary: Key Factors Affecting the Properties of FRC

- Fibers should have higher tensile strength and lower elongation percentage at break than the polymer, which is reinforced with fibers.
- Reinforcing efficiency of fibers is related to the orientation of fibers, their length, and volume fraction.
- Fibers need to have high surface free energy and be silanized for adhesion promotion to the polymer matrix.
- Fibers need to be well wetted and impregnated by the resin system.
- Fibers have to be adhered durably to the polymer matrix and the adhesion needs to have good hydrolytic stability.
- Optimal location for fibers in the construction is on the side of highest tensile stress.
- E-glass fibers exhibit the most promising and reliable reinforcement properties and clinical performance and should be preferred.

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Structural properties of dental FRC structures

3

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Chapter Outline

3.1 Introduction: Multiphase Composite Structures

Fiber-reinforced composite (FRC) is a multiphase material, as has been described in previous chapters. When dental constructions and devices are looked at as structures, it can be said that all of the constructions are composed not only of multiphase materials, but of combinations of different kinds of multiphase materials (Vallittu and Sevelius, 2000). Crowns and especially fixed dental prosthesis are affected by high stresses from occlusal loads, and cosmetically the most suitable materials are typically weak to withstand heavy occlusal loads. Therefore, dating back to early dentistry, framework for fixed dental prostheses (FDPs) was made of stronger materials like metal and veneered with acrylics, resin composites, or dental porcelain of tooth shade and color. In the time of nonmetallic materials, the alternative materials

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are zirconia veneered with porcelain, or monolithical zirconia and FRC veneered with particulate filler resin composite. A good example of a restoration that is affected by heavy loads is FRC FDPs, which has the load-bearing framework made of continuous unidirectional FRC with a veneer of particulate filler resin composite. A distinction should be made between FRC FDPs of this kind and those made for provisional use (Nohrström et al., 2000). When the fixed dental prosthesis is adhesively luted to teeth, there is a material combination of FRC—veneering composite—luting cement composite—tooth. It is obvious that the function of such a complex structure is largely dependent upon the quality of adhesive interfaces between the materials. Adhesive interfaces transfer stress from the occlusal loads to be carried by the durable FRC framework and finally by the abutment teeth.

The adhesive interface of resin materials and FRC can be based on adhesion and reactions between the polymer matrix of the FRC, or between the inorganic glass fibers if they are exposed on the FRC surface. With regard to the polymer matrix, the polymeric structure (thermoset or thermoplastic) and age of the polymer matrix influences the type of interfacial adhesion (Kallio et al., 2001; Lastumäki et al., 2002, 2003). On the other hand, if the focus of the adhesion is in the exposed glass fibers, utilization of silane coupling agents is necessary. Long-term hydrolytic durability in water containing environment of oral cavity in both cases has to be ensured.

Bonding of veneering resin composite, i.e., particulate filler composite (PFC), is important when the multiphasic dental construction is considered as such, but also when the construction is luted to the abutment and the load transfer from surface of the construction to the FRC framework and tooth is required to happen. Thus, bonding of resin composite luting cement to the restoration (so-called technical bonding) and bonding of the resin composite luting cement to the enamel and dentine (so-called technical-biological bonding) are important, as is the internal bonding interfaces of the dental construction (Fig. 3.1). Bonding aspects are important also in root canal post and bilayered restorative filling applications. FRC as a bonding substrate contains two types of materials: polymers and inorganic glass fibers and particulate fillers. Adhesives, i.e., monomers of dental adhesives, monomers of PFCs resin, and monomers of resin composite luting cements, do also have a significant role in achieving a durable bond between materials. It needs to be emphasized that there are two adhesive interfaces in the indirectly made restorations, namely one from cement toward restoration, and another from cement toward enamel and/or dentine. If the restoration is a direct restoration, there is one adhesive interface less in the system. Direct restoration requires therefore less space, which clinically speaking is often a very important aspect in the decision-making for type of treatment.

3.2 Secondary IPN Bonding

Bonding of polymer based dental materials can occur in two ways. When non-cross-linked polymers (linear polymers, thermoplastics) like denture base

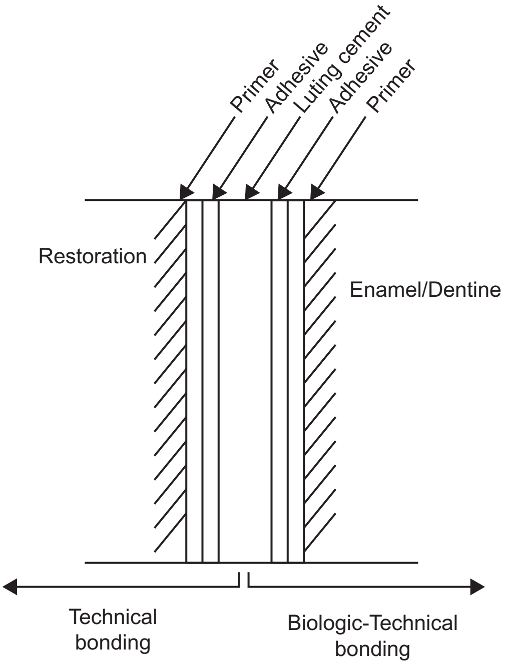

Figure 3.1 Interface structure of indirectly made restoration to the tooth surface. There are two adhesive interfaces, one toward the restoration (technical bonding) and another towards tooth (technical-biological bonding). The third type of bonding is biological bonding based on activity of cells, which exists, e.g., in osseointergtrated implants.

polymethylmethacrylate are bonded to the repair acrylic resin, bonding is based on dissolution of the pieces of denture base polymer with the monomers of the repair acrylic resin. Monomers of methylmethacrylate can easily dissolve the surface layer of predominantly non-cross-linked denture base polymers and after the repair resin has been polymerized, a durable bond between the new and old poly(methyl methacrylate) (PMMA) has formed, but without any chemical polymerization reactions between the new and old resin materials (Fig. 3.2) (Vallittu et al., 1994a, 1995b; Perea et al., 2014). Dissolution requires the solubility parameters of the linear polymer of the substrate to be close to those of the monomers of the new resin (Sperling, 1986; Barton, 1991). Solubility parameters have been developed to provide a method of predicting and correlating the cohesive and adhesive properties of materials. The numerical value of solubility parameter illustrates the amount of energy required to separate molecules. Two materials with similar solubility parameter values gain sufficient energy on mutual dispersion to permit mixing, which is essential for interdiffusion of monomers and swelling of the polymer surface. To differentiate the Interpenetrating polymer network (IPN), which is occurring at the interface of materials from that

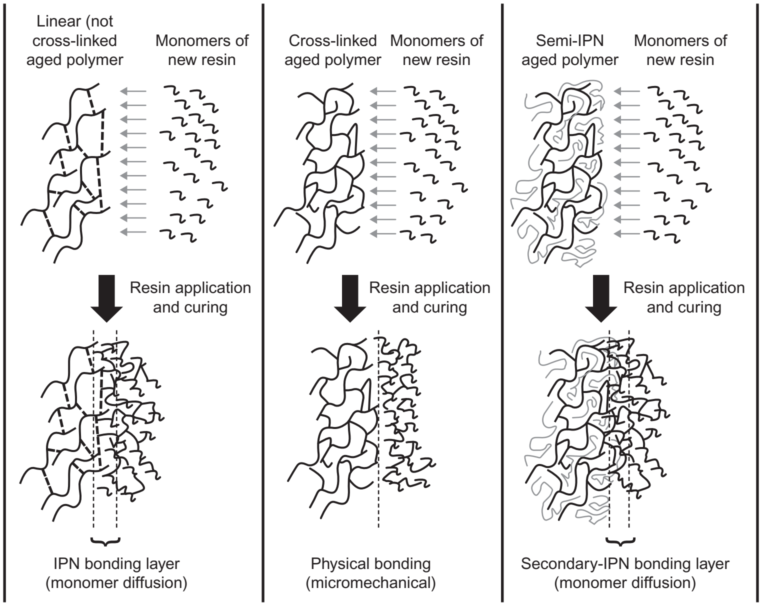

Figure 3.2 Mechanisms of bonding between non-cross-linked, cross-linked and IPN polymers and monomers of new resin system.

IPN which is the polymer matrix of the advanced FRC, the first one is called secondary IPN. Secondary IPN bonding is typically also found between resin denture teeth and denture base polymers.

3.3 Free Radical Polymerization Bonding

It is well known that in bonding of increments of dental filling resin composite during cavity filling is based on free radical polymerization between the oxygen inhibited resin layer and the new resin composite. During polymerization of the first increment, there will be high affinity of oxygen molecules to the radicals of the monomers on the surface of the composite increment and to the certain depth, oxygen molecules are spontaneously trapping the radicals (Al Musa and Al Nahedh, 2015; Bijelic-Donova et al., 2015). Once the new resin composite layer has been adapted to the oxygen inhibited layer and the new resin is polymerized, typically by light initiation, the oxygen inhibited layer will also become polymerized. Thus, the new resin composite layer is bonded by free radical polymerization to the substrate below (Fig. 3.3). Free radical bonding can also occur with FRC materials, when the veneering of the FRC framework is made without time delay, contamination or grinding of the oxygen inhibited layer on the FRC surface.

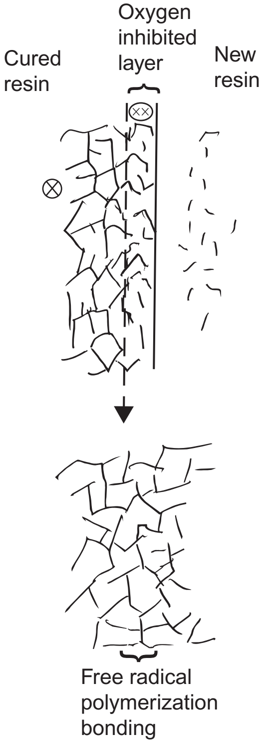

Figure 3.3 Free radical bonding occurs between fresh oxygen inhibited resin layer of resins and resin composites.

3.4 Bonding of Aged Polymers and Resin Composites

Ageing of linear polymers like polymethylmethacrylate do not change their bonding properties. Pieces of fractured dentures can equally be repaired and bonded to repair acrylic, regardless of the age of the denture (Vallittu et al., 1994a). On the other hand, when cross-linked polymers, like dimethacrylate based filling or veneering composites, light-cured denture base materials (e.g., Triad) or cross-linked polymer matrices of FRCs (typically prefabricated root canal posts and frameworks of FDPs which have not IPN polymer structure) are considered, the bonding is more challenging to be made without using the micromechanical retention for bonding (Kallio et al., 2001, 2013, 2014). The curing process of dimethacrylate monomers begins by chemical or light initiator systems and 80–90% of the final degree of monomer conversion (DC%) by light curing is reached within a few minutes of the start of the curing. Thereafter, curing will continue to the level that can be reached with light or chemical curing systems in those circumstances. After light curing, the DC% for dimethacrylate based resin composites is c.55%–65%, which means that 35%–45% of the double bonds of the methacrylate monomers have not reacted (Fronza et al., 2015). The majority of unreacted monomers are so-called pendant unreacted methacrylate groups, which means that only one group has reacted and attached the monomer to the cross-linked polymer backbone structure (Fig. 3.2). A minor percentage of monomers are completely unreacted as residual monomers. Despite the presence of many potential methacrylate groups in the polymer structure, they are not useable for bonding purposes due to the location and spatial configuration in the polymer backbone structure. Probability of having free radical polymerization between unreacted methacrylate groups and new resin monomers on the surface layer is very limited and therefore bonding of aged cross-linked polymers and composites cannot be obtained adequately by free radical polymerization, which would have ended the covalent bonding between the materials. Clinically, the poor bonding of aged cross-linked polymers to new resin materials can be seen in repairs of old composite fillings, bonding of prefabricated FRC root canal posts, and repairs of composite veneers which all will have discolored bonding interfaces and frequently occurring interfacial debonding. The benefits of so-called composite primers in enhancing adhesion between the aged composite and new resin composites are minor (Tezvergil et al., 2004; Perea et al., 2015).

It is important to note that covalently bound cross-linked polymer is not soluble, only the swelling of the intimate surface layer by appropriate solvents may occur. This means that secondary IPN bonding, which is based on dissolving and swelling the polymer substrate surface and diffusion of monomers of the new resin cannot occur, and thus, the interfacial bonding is weak. On the contrary, if the cross-linked polymer structure has been modified to be IPN in structure by incorporation of macromolecules (polymer chains) of, e.g., polymethylmethacrylate, dissolving of the substrate surface occurs and the secondary IPN layer for bonding is formed. Of FRC materials, there are products (by Stick Tech—GC Group), which have IPN polymer matrix between the reinforcing fibers (Fig. 3.2).

In some cases, the inorganic phases of the FRC, namely glass fibers' longitudinal surface or fiber ends, may be exposed to be the bonding substrate. As an average, half of the surface area of the FRC substrate can be of exposed inorganic glass and half is polymer matrix. A commonly used method to enhance adhesion of resin systems to the inorganic OH-covered substrates like glass fibers is based on using silane coupling agents, as has been described above (Rosen, 1978; Matinlinna et al., 2007). This would suggest that the bonding of the new resin materials to the surface of FRC with exposed glass fibers could be based on silane coupling agents rather than dissolution mechanism (secondary IPN bonding) polymer substrate or free radical polymerization. However, because the poor hydrolytic stability of the chair-side made silane promoted bonding, the silane promoted adhesion is not long lasting and will be deteriorated after water from saliva has absorbed to the polymer matrix and silane promoted interface (Heikkinen et al., 2013). Thus, the reliable and stable bonding mechanism between the FRC substrates and new resin systems are based either on secondary IPN bonding or free radical polymerization with the presence of oxygen inhibited resin layer on the surface of the substrate.

3.5 Structural Features of FRC Removable Dentures

Research on dental FRCs started in early 1960s when the first experiments on using glass fibers in denture base polymers were made. Besides using glass fibers, some tests were made to reinforce denture base polymers by carbon/graphite fibers. Little attention was based during that time on the low reinforcing effect of any fiber when they were used with powder-liquid type denture base resins. In 1990s studies were published which showed that the highly viscous resin mixture of PMMA powder and monomer liquid was not able to adequately impregnate the fiber. The use of the excess of the monomer liquid to lower the viscosity of the resin mixture did not resolve the problem (Vallittu, 1994, 1995b). The higher quantity of monomer liquid in the resin mixture caused void and gap formation to the composite by polymerization contraction. This led to the development of the polymer preimpregnation system of the reinforcing fiber with porous PMMA. Porous PMMA between the silanized glass fibers function as polymer powder functions in the denture base acrylic resin mixture with MMA monomer liquid. Presence of PMMA lowers the polymerization shrinkage of the resin and this can be seen in denture base resins and also between the fibers if the fibers were preimpregnated with PMMA.

The fiber-reinforcements in denture bases are divided into two categories. Ladizesky and co-workers reported a method where fiber weaves were distributed through the entire denture base plate (Ladizesky et al., 1994). On the other hand, the approach by Vallittu is based on the concept that only the weakest part of the denture base (location of fracture initiation) is reinforced by fiber reinforcement. Two reinforcing concepts are referred to as total fiber reinforcement (TFR) and partial fiber reinforcement (PFR) (Fig. 3.4) (Narva et al., 2001). Clinical studies have been performed with FRC reinforced removable dentures which suggested that PFR offers an effective method for eliminating fractures in denture base, as demonstrated earlier (Narva et al., 2001).

The successful use of PFR requires correct positioning of the fibers in the denture base. Based on the laboratory experiment, continuous unidirectional glass fibers can considerably increase fatigue resistance of removable complete and partial acrylic dentures (Vallittu et al., 1994b, 1994c, 1996). More detailed laboratory investigations showed the importance of the location of the fibers in mechanical behavior. In a static deflection test with denture base polymer the influence of fiber location was somewhat less than in dynamic testing which measured fatigue behavior of the material (Narva et al., 2005a, 2005b). In impact force testing, which simulates dropping of a denture to a hard surface, an improved impact strength of the material by incorporation of glass and aramid fibers to the denture base polymer was demonstrated (Vallittu et al., 1995; Vallittu and Narva, 1997). Fiber reinforcement absorbs the impact energy and provides better resistance for the denture against dropping.

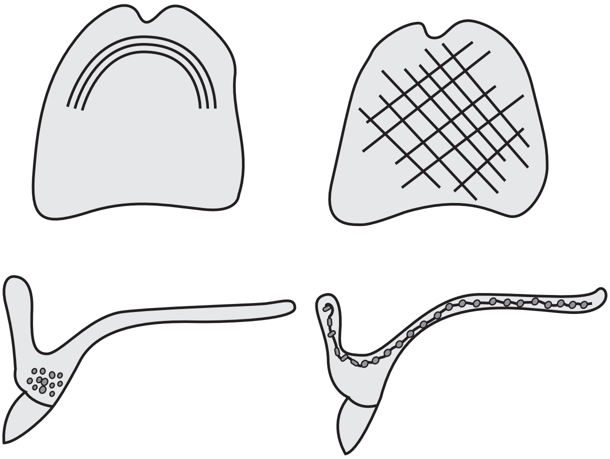

Figure 3.4 Schematic presentation of total fiber reinforcement (TFR) of continuous unidirectional glass fibers under the denture teeth and partial fiber reinforcement (PFR) of woven fibers of whole denture base plate of an upper complete denture.

The fibers of the PFR should be placed to the region on the denture base where the fracture most likely begins, i.e., the region of the highest tensile stress during masticatory function (Fig. 3.4). The correct place for the fibers in upper complete dentures is close to the denture teeth, and fibers should be directed along the ridge lap in a horseshoe shape (Narva et al., 2001). Continuous unidirectional fibers offer the highest resistance against midline fractures of upper complete dentures. In removable partial dentures, where the fracture likely occurs in the anterior margin of the denture, the fibers in the form of woven fabric are preferred. Woven fiber fabric with two-dimensional fiber direction divides the reinforcing effect to several directions and therefore is the preferred type of reinforcement if the potential fracture path cannot exactly be defined. An average of 7—10 mm wide FRC reinforced region with woven glass fiber fabric eliminates the denture fracture initiations and propaganation in upper removable partial dentures. Overdentures are also reinforced with woven fibers to eliminate cracks and fractures of denture base polymer close to precision attachments (matrix part) of dentures. It has been suggested that FRC can also lower the number of loosenings of the matrix parts of precision attachments. More about the clinical and technical aspects of FRC removable dentures are described in Part II of this book.

3.6 Structural Features of FRC Fixed Dental Prostheses

Fixed dental prostheses made of FRC are classified to surface retained FDPs, inlay/onlay retained prosthesis, full coverage crown retained prosthesis and hybrid prosthesis (Vallittu and Sevelius, 2000). The latter type is a combination of various retaining elements according to the specific need of the dentition. Although FRC fixed dental prostheses can be made directly or indirectly, their design principles are similar. Implant supported prostheses have been fabricated from carbon/graphite FRC and glass FRC but they have not yet gained more popular use (Ekstrand et al., 1987).

FRC fixed dental prostheses have a load-bearing framework made of continuous unidirectional fibers which is veneered with veneering resin composite, or acrylic resin in the case of implant supported prostheses. Veneering composite is bonded to the framework preferably with secondary IPN mechanisms but also with free radical polymerization mechanisms. All indirectly made tooth supported FRC prosthesis has to be luted with composite resin luting cements. Direct FRC prosthesis can be bonded to the tooth by polymerization of restorative composite resins. In the FRC prosthesis, the framework between the abutments is made of continuous unidirectional fibers, which offer high flexural strength and load-bearing capacity (Dyer et al., 2005; Özcan et al., 2005). Single composite crowns can be reinforced with woven bidirectional continuous fibers which form the coping for the crown and are covered with veneering resin composite. A specific feature of the FRC FDPs design is that the pontics, both in the anterior and the posterior area, need to be reinforced with additional fiber to eliminate risk of delamination of the pontics from the framework (Fig. 3.5) (Xie et al., 2007).

Surface retained resin bonded FDPs are supported and bonded from both ends or from one end only. In the surface retained FRC FDPs, the location of bonding wing in vertical dimension of the abutment is important. Fibers of the bonding wing should be placed close to the incisal edge to eliminate the momentary forces for dislodgement. On the other hand, the bonding wing needs to cover largely the bonding surface of the abutment. The bonding wing is placed most often to the oral surfaces of abutments (palatal and lingual) but also labial and buccal surfaces can be used if there is limited space in the oral surface. To protect the fibers of the bonding wings, a layer of PFR is placed to cover the wings.

In connectors, the continuous unidirectional fibers should have a cross-sectional design, which offers good resistance against occlusal forces. It has been shown that thickness (palatal/lingual-buccal direction) of the connector versus width of the connector is an important parameter when stiffness and strength is optimized, which is required for the clinically long-lasting restoration. Normally the cross-section of the connector has maximal quantity of fibers in volume, but if the there is an excess of space, the highest strength is provided by placing the fibers on the tension side of the connector and use the remaining space for the veneering resin composite. The thickness of the connector of upper anterior resin bonded FRC FDPs cannot be emphasized too much. In some case minor additional approximal cavities are suggested to maximize the strength (thickness) of the connector (Fig. 3.6).

Inlay/onlay retained fixed dental prostheses are made by placing continuous unidirectional fibers running from cavity to cavity. The prosthesis can be made indirectly or directly. In the case of indirect FDPs, cementation is made with composite resin luting cements, which contains regular adhesive resin, which is used to

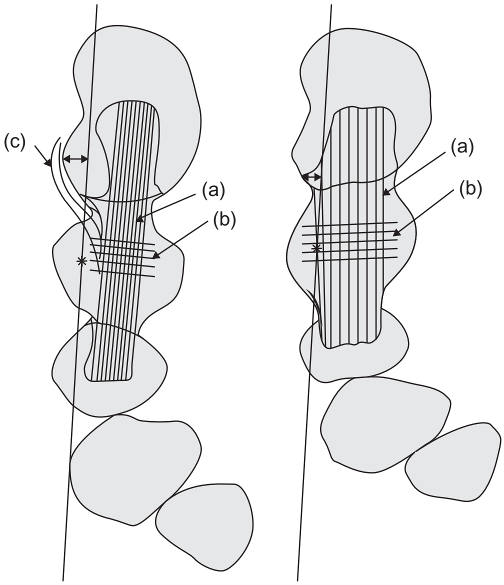

Figure 3.5 Framework design for FRC fixed dental prosthesis (inlay and hybrid prosthesis) in the posterior region contains the following parts: (a) main framework, (b) pontic reinforcement, and (c) optional surface bonding wing if the cavity is of wide enough to exceed bucco-lingually/palatinally the line occlusal loading contact point (*) of the pontic (*arrow*).

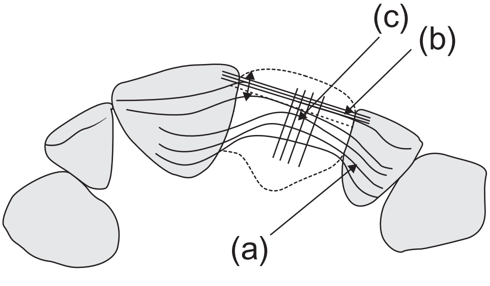

Figure 3.6 Anterior FRC fixed dental prosthesis contains the following parts: (a) main framework, (b) optional extra framework to increase labio-palatinal thickness of the connector (*arrow*), and (c) pontic reinforcement.

activate the bonding surface for secondary IPN bonding. Self-adhesive adhesives of cements do not provide optimal bonding to the framework, although they may work well on dentine. If the prosthesis is bonded to the canine, it is recommended to add an additional bonding wing buccally or palatinally to the framework to avoid loosening of the inlay in cuspid protected articulation. In the case of existing old fillings in abutments, removal of fillings provides space for the FRC framework and veneering composite resin. In posterior restorations (premolars and molars) adequate vertical support against occlusal loads are always needed, and therefore, in intact teeth, an approximal box preparation depth of more than 1.5 mm provides support for the prosthesis if the fibers are accurately placed into the box-shaped cavity. The load-bearing capacity of such an inlay fixed dental prosthesis is high, up to 2600 N, which is considerably higher than maximal biting forces in the molar region, i.e., 800 N. Veneering of the FRC framework is made by laboratory veneering composite resin or by restorative composite resin in the direct restorations. Optimal thickness of the veneering composite resin on the occlusal surface of FRC framework is more than 1.5 mm (Garoushi et al., 2006a). Clinically, the FRC FDPs have showed good performance, which will be discussed more in Part II of this book.

Full coverage crown retained fixed dental prostheses are made by layering woven FRC on prepared abutments for fabricating the copings. Abutments are connected with continuous unidirectional fibers which run from one occlusal surface of coping to another. Adding additional pieces FRC in perpendicular direction to the fibers of the main framework are used to support the cusps of the pontics. Veneering is made with laboratory PFC resin. The FRC framework is fully covered by veneering composite resin in order to obtain a polishable and tooth colored surface. Special attention needs to be paid to the interproximal regions for esthetic-cosmetic reasons. If the FRC framework is not properly covered by the veneering composite resin, or preferably opaque paint, the darkness of the oral cavity can be visually transmitted through the connectors and cause problems with the appearance of the restoration.

FRCs can also be used as reinforcements of provisional fixed dental prosthesis during fabrication of conventional FDPs. In provisional FDPs, provisional automix or powder-liquid acrylic resins are reinforced with glass fibers. More about FRC fixed dental prostheses and their clinical use is described in the Part II of this book.

3.7 Structural Features of Root Canal Post Systems

The use of FRC in root-canal posts to anchor cores and crowns has rapidly increased since the introduction of “fiber posts” in the late 1980s (Fokkinga et al., 2006; Mitov et al., 2014; Saker and Özcan 2015). FRC can be used in root canal as prefabricated solid posts and individually formed posts. Prefabricated posts are available in various diameters, typically of 1.2, 1.4, and 1.6 mm. When design of the postcore systems follows the principles of the time of metallic posts, the use of prefabricated FRC posts may be justified. However, according to present understanding, the biomechanics of the tooth should be considered carefully to eliminate root fractures and other later related complications such as post loosening and secondary caries. Therefore, focus should be put to the use of individually formed FRC posts instead of prefabricated fiber posts. Individually formed posts should be preferred especially in flared root canal (Xie et al., 2009; Hatta et al., 2011; Xu et al., 2015).

The prefabricated solid FRC posts of various diameters are made of reinforcing fibers (carbon/graphite, glass, quartz) and polymerized resin matrix of epoxy polymers or dimethacrylates between the fibers. Individually formed posts are made of nonpolymerized fiber-resin prepregs, consisting typically of glass fibers and a light-curing resin matrix, preferably of that kind which forms a semi-IPN matrix after curing. The rationale of the individually formed FRC post is to fill the entire space of the root canal with FRC material to respond better to the loading conditions by the masticatory system (Vallittu, 2016). The increased fiber quantity, especially in the coronal part of the root canal, increases the load-bearing capacity of the system, and the biomechanics of a tooth can better be simulated because the fibers are located closer to the dentine, where highest stresses exist. This aspect is demonstrated with finite element (FE) modeling later in this chapter.

A tooth restored with a root canal posts system should be able to withstand cyclic loading of high magnitude for a long period of time without catastrophic failure or marginal breakdown of the crown, which can predispose to the secondary caries. The load-bearing phase of the root canal post system, i.e., the FRC root canal post, should withstand the loads and retain the crown margins intact. Repeated stress cycles cause microscopic cracks mainly in the tension side of the construction and, after a period of time, a number of cracks increase to such a size that a sudden fracture can occur even with a low stress level. Clinically, the material based weakness in fatigue resistance is compensated for by designing and dimensioning the former time period's cast metal postcore and crown ferrule correctly, or by using the novel concept of individually formed FRC post-and-core systems, which increases the quantity of reinforcing fibers in the cervical part of the tooth. This approach should be taken into consideration by fabricating the individually formed post instead of using prefabricated FRC post. Use of single thin prefabricated FRC posts should be limited, especially due to their poor capacity to resist loads by the masticatory forces.

Solid prefabricated FRC posts have certain shortcomings which lower their clinical function and are due to their polymer matrix composition. Fabrication of solid prefabricated FRC root canal posts is based on impregnation of fibers with thermoset resins, like dimethacrylate or epoxy resins and achieving a high degree of cure for the resin matrix. Thermoset resins which form a cross-linked polymer matrix between the fibers do not allow for good bonding of post to resin cement and core-build-up composites due to lack of free radical polymerization bonding sites on the post surface, and lack of possibility for secondary IPN bonding. To overcome the problem of bonding and adhesion, some manufacturers have added serrations to the post for mechanical retention of the cement. These may improve mechanical retention vertically, but they do not allow load transfer from the post to dentine to occur when lateral and oblique forces are applied to the crown. On the other hand, if the semi-IPN polymer matrix is used between the fibers, as can be the case in individually formed posts, adhesion of the post to cement is good (Mannocci et al., 2005, Wolf et al., 2012). It has been shown by radioactive labeled resins that monomers of an adhesive resin diffused to the semi-IPN polymer matrix of the post to a depth of 25 μm in few minutes. Bonding of individually formed

FRC posts to the luting cement is also ensured by free radical polymerization bonding. The resins should also enable complete impregnation of fibers. There are some solid prefabricated FRC root canal posts on the market which do not entirely fulfill the requirement of complete impregnation, and thus the strength of the post is lower than expected (Lassila et al., 2004). More of the root FRC root canal post and their clinical use are described in Part II of this book.

3.8 Structural Features of FRC Fillings

Utilization of discontinuous FRCs in filling composites has been studied for many years (Garoushi et al., 2006a, 2006b). Reasons for poor success of using FRC filling composites in the 1990s were the selection of too-short fibers (below the critical fiber length), which were not able to increase the strength and toughness of the composite resin. In addition, short discontinuous FRC filling material was used as bulk material and it demonstrated poor polishability and high wear rate. The current concept of using FRC material in filling is based on using FRC base with relatively long discontinuous fibers and veneer the base with conventional particulate filler resin composite. It has been shown that fibers' orientation perpendicular to the axial walls of a cavity reduces polymerization contraction of the composite. In dental fillings, the concept of using fiber-controlled polymerization contraction is based on using discontinuous fibers with an average length of 0.7–0.9 mm. In the fiber distribution, there are also longer fibers present which exceed considerably the critical fiber length and have an impact on the strength and toughness of the composite. Packing the fibers to the cavity forces the fibers to orientate randomly in a plane, which controls the curing contraction where the fibers contact the axial walls of the cavity, and improves the sealing of the restoration to cavity walls (Tezvergil-Mutluay and Vallittu, 2014).

Another benefit of using FRC base for filling composites is the increase of the toughness of the composite filling. Toughness and other physical properties are superior compared to the properties of conventional filling composites (Garoushi et al., 2012). The function of the FRC base for filling composites is to support the filling composite layer and serve as a crack prevention layer. More about FRC filling composites is described in the Part II of the book.

3.9 Findings by Finite Element Analysis of FRC Structures

The FE method has become one of the most frequently used analyzing methods when evaluating biomechanical phenomena such as an inner stress, deformation, and strain on dental materials and tissues. Unlike with many other FE applications, certain assumptions need to be made when dealing with a complicated set of root, bone, or dental restorative and prosthetic devices. In FE analysis, a large structure divided into a number of small, simple-shaped elements can be more easily calculated than a whole undivided large structure. Using the traditional biophysical knowledge database in a rational validation process, the use of FE analysis in the dental field has been significantly refined during the last decade (Shinya et al., 2008a, 2009a; Hasegawa et al., 2013; Hase et al., 2014). However, for instance, fixed prosthesis cannot be assimilated to a simplified geometric representation due to both their anatomical shape and layered structure. Sophisticated techniques have therefore been developed to refine geometry acquisition, such as recreation and digitization.

Designs of FRC framework for FDPs have been extensively investigated using FE method and stress analysis, clarifying that the reinforcement effects differ and depend on the position of the FRC framework in the prostheses. An important factor in the designing of FRC FDPs is that the FRC framework should be located at sites at which there is occurrence of tensile stress, and that the fibers are embedded in a form so as to follow the direction of tensile stress from the results of FE analysis (Shinya et al., 2004). The difference in the function of anterior and posterior teeth and related stress distribution needs to be considered when designing the FRC FDPs (Fig. 3.7A, and B).

In anterior FDPs, high stress concentration was observed in the connector area under all occlusal loading conditions, which might be attributable to the isotropic properties of veneering composite and the intrinsic morphology of anterior prostheses. Higher stress concentration at the connector was decreased when the framework material was changed form metal to glass FRC. In general, the tensile stress was oriented from the lingual side to the connector at the abutment tooth. At the connector of the FDPs, the tensile stress was oriented from the marginal ridge of the abutment tooth (missing tooth side) to the labial side of the pontic, showing a curvature along the external form of the labial side of the pontic. (Figs. 3.8 and 3.9) (Shinya et al., 2008b; Yokoyama et al., 2009, 2012).

In posterior FDPs, high stress concentration was observed in the connector area as found also with anterior prosthesis. The tensile stress distribution was simple because the direction of occlusal force is mainly applied vertically. In general, tensile stress was oriented from the lower embrasure of connector to the occlusal surface of abutment teeth, and then to the marginal area parallel to the external form of FPD. At the pontic, tensile stress was oriented from the upper embrasure of connector (or marginal ridge of pontic) to the pontic base, showing a curvature along the external form of pontic bottom shape. As a whole, tensile stress showed a

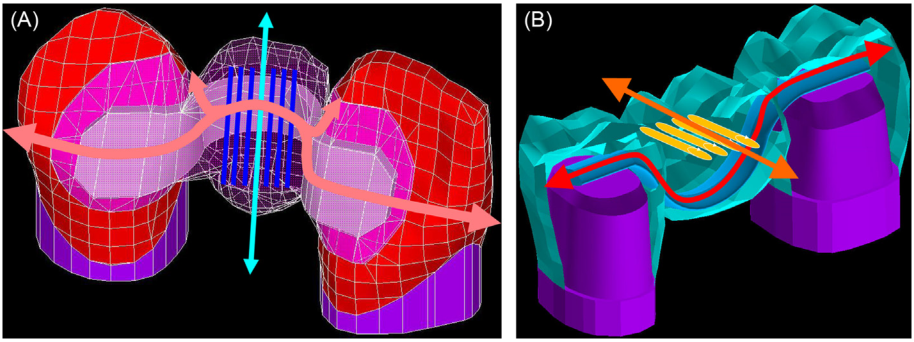

Figure 3.7 Finite element model image demonstrating location of tensile stress and its direction in (A) anterior and (B) posterior FRC fixed dental prosthesis. Note the additional FRC reinforcements which are crossing the FRC main framework between the abutments.

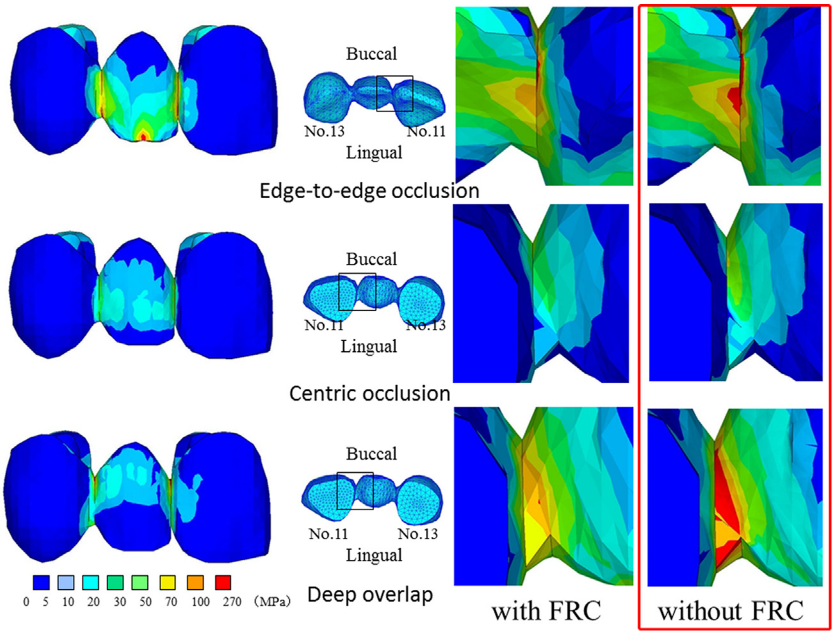

Figure 3.8 Finite element model image of stress distribution of anterior fixed dental prosthesis. On the left hand side: buccal view; on the right hand side a prostheses without FRC substructure. *Red color* demonstrates the highest tensile stress.

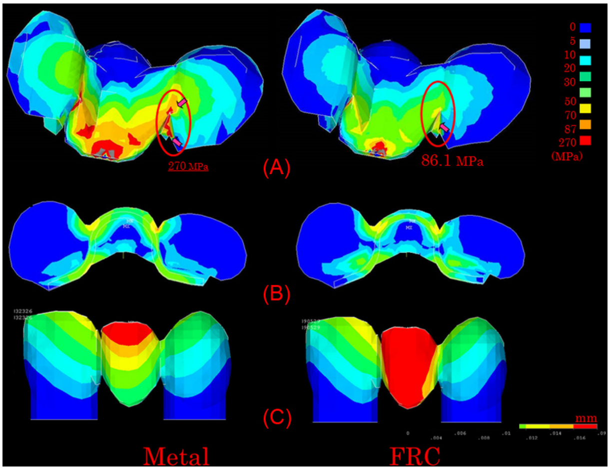

Figure 3.9 Finite element model image of stress distribution of anterior adhesive fixed dental prostheses: On the left: metal framework fixed dental prosthesis; on the left: FRC framework fixed dental prosthesis. (A) lingual view, (B) cross-sectional view, (C) labial view with abutment teeth.

M-shaped stress distribution pattern, i.e., connecting the proximal margins of both abutment teeth and being oriented parallel to the external form of bridge near the outer surface. A trend was observed in which more parallel direction of the fibers was able to reduce the magnitude of tensile stress (Figs. 3.10, 3.11 and 3.12) (Ootaki et al., 2007; Aida et al., 2011; Shinya et al., 2009b).

Root canal posts applications have also been studied by FE method. Calculations have earlier demonstrated high levels of stress inside of the tooth when metal posts are used. Thus, the metal posts predispose root fractures after repeated loading

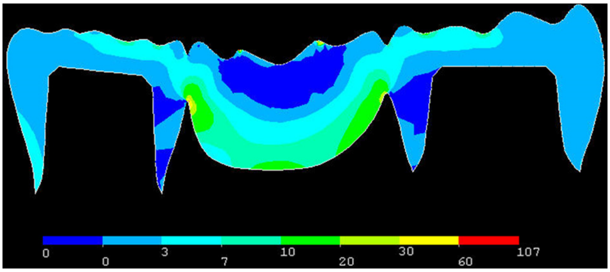

Figure 3.10 Finite element model image of stress distribution of posterior fixed dental prosthesis without FRC substructure. Image shows highest stress concentration at the lower surface of connector.

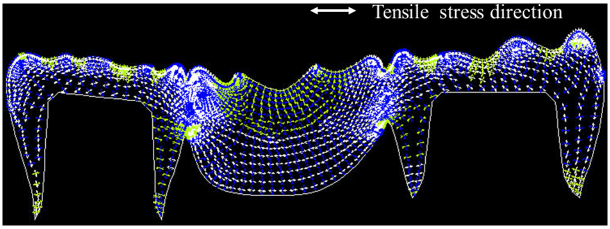

Figure 3.11 Finite element model image of stress distribution of posterior fixed dental prosthesis, white arrows in the prostheses show direction of tensile stress.

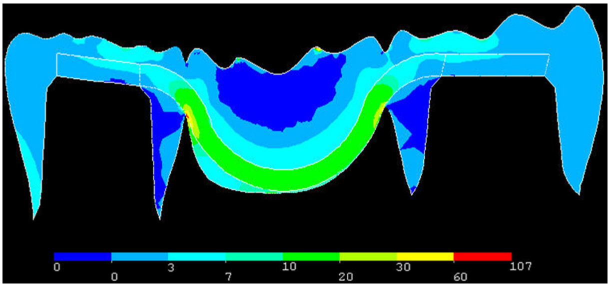

Figure 3.12 Finite element model image of stress distribution of posterior fixed dental prosthesis with FRC substructure. FRC substructure decreases the stress concentrations and the tensile stress can mostly be found in the reinforcing FRC substructure.

cycles. On the other hand, if thin prefabricated FRC posts are used, the cervical area of tooth is affected by tensile stress showing the low volume of the post material does not mechanically support the tooth-core-crown system. By increasing the volume of the FRC material in the root canal and locating the fibers close to the dentine walls of the root canal, magnitude of tensile stress at the cervical part of the tooth is considerably lowered (Fig. 3.13). This demonstrates even stress distribution, which lowers the risk of marginal breakdown of the crown and secondary caries.

3.10 Future Trends

Future development of FRCs is focused on optimization of the design of the substructures in FRC devices. Attempts to develop the semi-IPN polymer matrix short glass FRC in filling material applications have been made. This is one field of future development for dental FRCs. Utilization of thinner fibers, so-called nano fibers can potentially be used in reinforcing the interfaces of resin composites and dentin, which would be biomimicking of the structure of the interface of enamel and dentine with collagen fiber protrusions. Incorporation of bioactive minerals to the reinforced resin

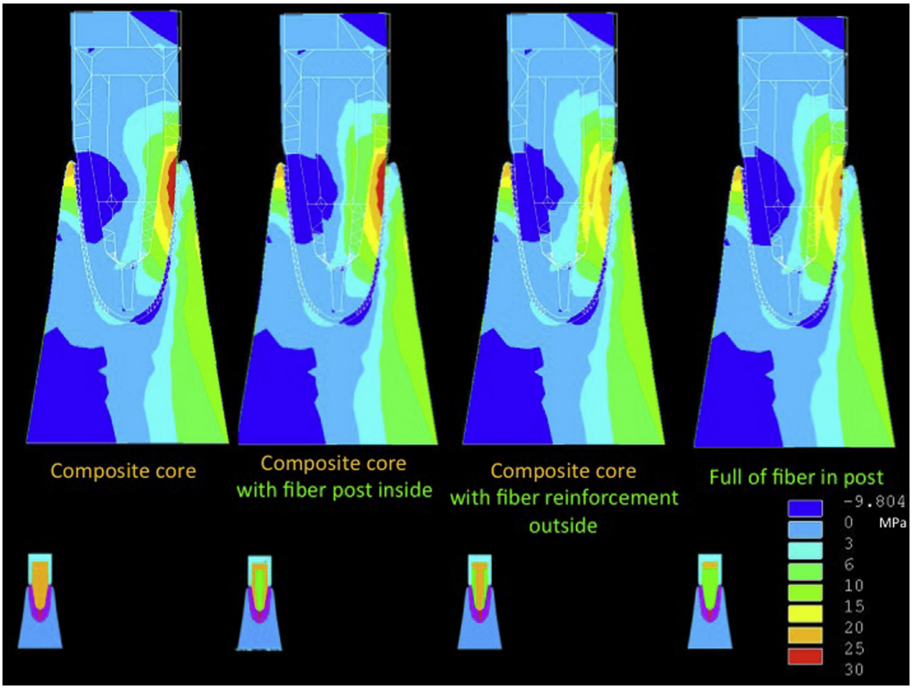

Figure 3.13 Finite element modeling images of root canal post systems: from the left: composite core without FRC post, with prefabricated fiber post, with individually formed FRC post (fibers close to dentin walls) and individually formed FRC post (root canal fully filled with FRC material). *Red color* demonstrates the highest tensile stress.

composites, and even to change to fiber binding matrix from resin base to inorganic type, are future developments that can change the nature of dental materials considerably in the future. Another field where FRCs are starting to be utilized is implantology and tissue engineering. There are promising results of using bioactive glass modified FRC in oral, orthopedic and head-and-neck implants and as tissue engineering scaffolds. (Fig. 3.14A, and B) (Aitasalo et al., 2014; Piitulainen et al., 2015).

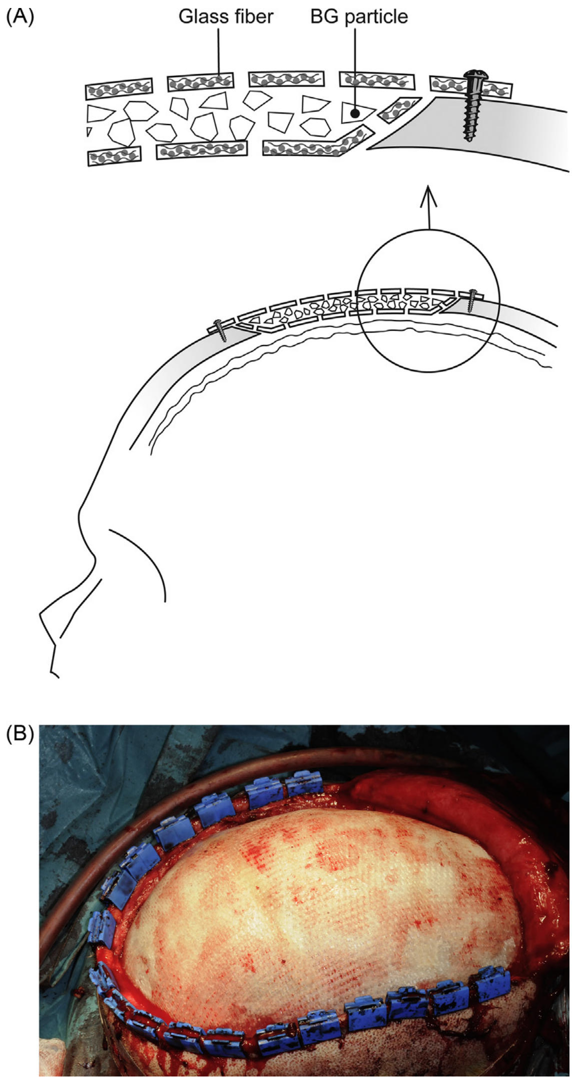

Figure 3.14 Glass FRC in combination with bioactive glass is used clinically in bone replacing implants like craniolplasty implants. (A) schematic structure of implant (BG = bioactive glass), (B) surgical operation of insert a FRC cranioplasty implant to replace missing part of cranial bone.

The nonmetallic nature of FRC as implant material is preferred due to causing no harm to magnetic resonance and cone-beam tomography imaging systems and enabling use of post operative radiation therapy through FRC implant, which cannot be done with metal implants. Benefits of FRC implants in long bone applications (orthopedic surgery) are in bone-like biomechanical properties of FRC which can eliminate stress shielding of bone by the implant. Incorporation of bioactive glass to the FRC material improves osteogenic properties of the implant and makes the implant antimicrobial.

3.11 Summary: Key Factors of Dental FRC Structures

- Dental FRC structures are combinations of resin and resin composites of various kinds.
- Load-bearing part of the system is made of FRC, veneered with veneering composite and adhesively luted to remaining teeth.
- Bonding of indirect restoration has two adhesive interfaces: one from cement toward the restoration and another from cement to dental tissues of dentine and enamel.
  - Monomers of adhesives and resin composite cements should be able dissolve the polymer matrix structure of FRC and form secondary IPN bonding.
- In removable partial dentures, the structural feature for reinforcing the denture is the PFR, i.e., only the location of fracture initiation is reinforced with fibers.
- In FDPs, the FRC can be used as reinforcement of temporary bridges and as a framework of veneered definitive long-term use bridges.
- In root canal post systems, the adhesion aspects of cements to post and volume of FRC post material in coronal root canal are important.
- In FRC filling systems, the structure of filling is a bilayered composite and the layer thickness of FRC substructure should be as high as possible whilst keeping 2 mm space for the occlusal hybrid composite.

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An overview of fixed dental prostheses and the dynamic treatment approach

4

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Chapter Outline

4.1 Prosthodontic Treatment Concept With FRC

Modern conservative dental treatment prefers minimal invasive options rather than the relatively destructive treatments used in the time of amalgam and gold alloys. Use of all-ceramic restorations still requires large preparations of tooth as well. Minimal invasive treatments became possible in restorative and prosthetic dentistry through the development of enamel and dentine bonding techniques, and through the improvement of restorative materials, especially resin composites. However, inadequate mechanical properties, especially flexural strength, fatigue strength, and toughness of resin composites made of particulate fillers, have limited their use in heavy load bearing areas in single restorations, and especially in fixed prostheses.

The decision to replace single or multiple teeth is the first determinant in treatment planning. The following aspects should be considered when the treatment plan is made: patients' wishes, age, local and systemic health considerations, masticatory function, appearance of the dentition, need for restoring of teeth in general, reversibility of the treatment, prognosis, economical issues (patients' and societies') (Fig. 4.1).

A group of materials whose mechanical properties can be tailored to specific needs is fiber-reinforced composites (FRCs). Physical properties and structure of FRCs are described in detail in Part I of this book. By using FRCs, fixed dental prostheses (FDPs) can today be made with minimal invasive technique, which means that combinations of various kinds of adhering and retentive elements of the fixed prostheses

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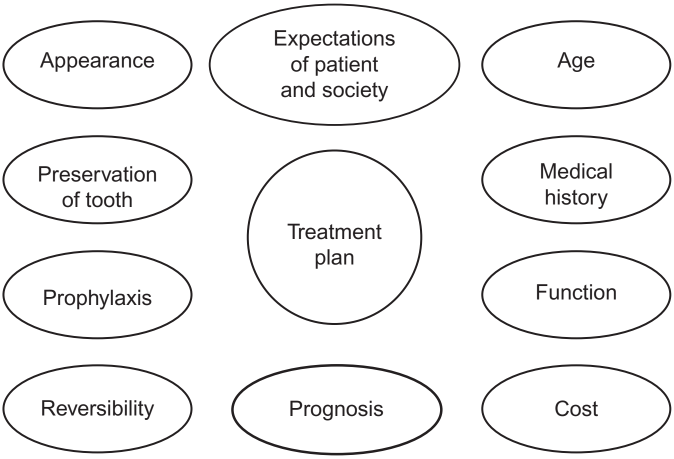

Figure 4.1 Several aspects need to be considered when the treatment plan for prosthetic rehabilitation is made.

could be incorporated in the prostheses. Use of FRC materials is also considered as biomimicking dentistry in which natural collagen-hydroxyapatite fiber composite of dentine is used together with manmade fiber composite (Soares et al., 2016). A selection of the adhesive elements like surface bonding wings, inlays, onlays, posts, and crowns can be used in one restoration if there is a clinical need for that kind of restoration of abutment tooth. Thus, optimally selected restoration of abutment can provide at the same time a retaining element for the FRC FDP. In practice, a resin bonded FRC FDPs, e.g., may contain inlays/onlays, surface bonding wings, and crowns. Classification of FRC FDP is (Vallittu and Sevelius, 2000):

- Provisional FRC FDP (provisional FDP resin and fiber reinforcement)
- Definitive FRC FDP (FRC framework veneered with veneering of restorative resin composite): Direct FDP, semidirect FPD, and indirect FDS:
  - surface retained
  - inlay/onlay retained
  - root canal post retained
  - surface retained
  - hybrid retained

Direct and indirect FRC FPDs can be made also immediately after extraction of tooth. In fabrication of immediate FRC FPDs, the resorption of marginal bone and recession of alveolar mucosa underneath the pontic can be controlled by exceeding the bottom of the pontic to the alveolar socket to the depth of c.1.5 mm.

In addition to the fabrication of various kinds of FRC FDPs, the FRCs can be used in the repair of existing conventional prosthetic devices. Repairs of veneers of porcelain-fused-to-metal restorations with resin composite veneers can be made by woven glass fiber reinforcement. Addition of woven glass fibers between the metal framework and resin composite veneer can increase the strength of the repair threefold (Vallittu, 2002; Özcan et al., 2006a). By appropriate repair of old restorations their functional life-time can be increased.

4.2 Dynamic Nature and Longevity of Fixed Prosthodontic Treatment

Prosthodontic treatment is the continuation of using several prosthodontics devices during the life-time of the patient. Presently, the prosthodontic challenge is dominated by the mindset of implant therapy and the alternatives of resin bonded and traditional FDPs are less often considered as a real treatment solution (Kuijs et al., 2016). The use of minimal invasive restorative dentistry and prosthodontics allows treatment of the patient by means of the dynamic treatment approach. In the dynamic treatment approach, the odontological, medical, and subjective needs of the patient can better be taken into consideration than in conventional fixed prosthodontics. Alternative treatment options later in life are permitted through selecting the dynamic treatment concept at the beginning. This means that the life-long treatment cycle is started with tooth substance preserving treatment modalities, not necessarily with conventional full coverage crown retained restorations. There is also increased demand from society to keep the treatment costs at low level, which has not always been possible with conventional tooth or implant supported prostheses. When prolonged functional life of existing restorations that need repair and maintenance care is aimed for, the dynamic treatment approach can be used by new indications for FRCs in repairs of existing old metal and metal ceramic restorations. Repairs with FRC material utilize high durability of FRC materials and tribochemical silica coating systems of metals and ceramics for bonding resin composites (Özcan et al., 2005, 2006b). “Repair rather than renewal” could be considered one of the principles of the dynamic treatment approach (Vallittu, 2003).

When traditional treatment concepts are considered for their expected functional life-time, one should differentiate between the longevity of the restoration itself and the potential damage to the abutment teeth and alveolar bone. Also, both the magnitude of extension of the FDPs and the labor and the costs of the FDPs are background factors to take into account when the functional life-time of the treatment is considered in terms of cost efficiency and ethics. The answer to the question “at least how long should the treatment outcome last?” is compelling.

Many studies have been undertaken to evaluate success rates and survival times (total and functional) of fixed prosthodontic treatments of different kinds. Definitions of treatment failures which have been reported in the literature may be highly variable. By ‘success’ it is meant that the FDPs is free of all complications over the observation period and by ‘survival’ that the prostheses is remaining in situ with or without modification for the observation period. Out of a total of 19 carefully selected studies on conventional FDPs, the 10-year risk of success was 71.1% (Tan et al., 2004). Caries, endodontic problems, and periodontal diseases were the most common biological complications, whereas loss of retention was the commonest technical complication. With regard to the implant retained FDPs, a systematic review of 21 studies showed a success rate of 61.3% for implant supported FDPs (Pjetursson et al., 2004). The study concluded that 38.7% of the patients had minor or major complications in the first 5 years after implantation. Biological complications were peri-implant mucosal lesions and peri-implantitis, and technical complications were veneer fracture and screw loosening or fracture. In the treatment failure of conventional tooth supported FDPs, damage of abutment teeth due to secondary caries will lead to a need for more extensive prosthodontic application. Although biological complication related failures of implant supported FDPs seldom cause damage to the adjacent teeth, biological effects of peri-implantitis to the jaw bone can be serious. Infection can cause severe

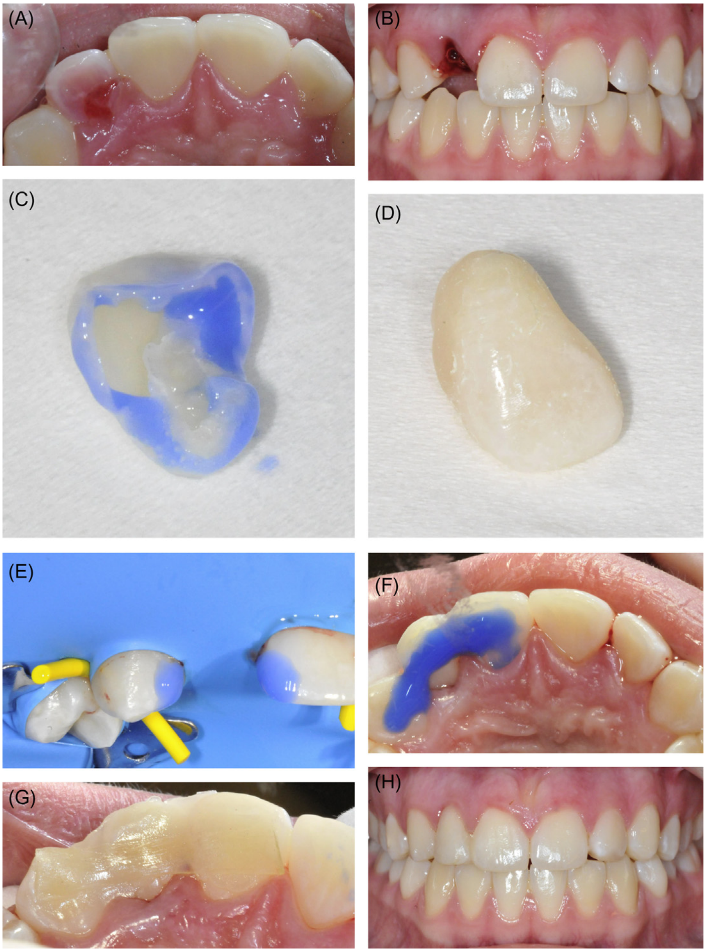

Figure 4.2 An example of beginning the dynamic prosthodontic treatment of resorbing lateral incisor of a girl at the age of 14 years. (A) occlusal view of incisal area, (B) extraction socket of D12, (C) extracted tooth is prepared to be pontic, (D) pontic ready for insertion, (E) abutment teeth are etched for adhering the ponti initially to the correct position with flowable resin composite, (F) palatal surface is etched for placing continuous unidirectional glass fibers (everStick C&B, Stick Tech−GC), (G) glass fibers in place before covering with restorative resin composite, (H) treatment outcome 7 weeks after extraction. The treatment enables all other prosthodontic treatment options in the future.

loss of alveolar bone and after removal the implant there is no bone left for the new implant. Loss of bone also compromises the fabrication of conventional FDPs.

By selecting a treatment approach of a dynamic nature, the treatment of a partially edentulous patient begins with surface retained and inlay retained restorations. Fig. 4.2 shows an example of the first prosthodontic treatment of a girl at the age of 14 years. Severely resorbing lateral incisor tooth was replaced by a direct surface retained FRC bridge with a natural crown and a pontic. The treatment was made immediately after extraction of the resorbing tooth. The principles of selecting and designing the prostheses and the longevity of FRC FPD treatments are described more in detail in the next chapters of this book.

4.3 Conclusions

Prosthodontic treatment is not one single treatment during the life-time of the patient. It is continuation of several different kinds of restorative and prosthodontics dental treatments. The dynamic treatment approach is an approach that begins with the least magnitude of damage to the remaining teeth but provides definitive tooth replacing restorations for the patients. FRC materials are well suited to the dynamic treatment approach due to their high mechanical strength and versatile clinical indications. Although an increased number of partially edentulous elderly patients with a demand for good quality of life is one particular group of patients receiving great benefit from FRC FDPs, all groups of patients from young to old can successfully be treated with FRC FPDs and other FRC restorations.

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Fabrication of indirect fiber reinforced resin composite (FRC) dental devices

5

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Chapter Outline

5.1 Introduction

The durability of fiber-reinforced composite (FRC) fixed dental prostheses (FDPs) are dictated by a number of factors such as the mechanical properties of FRCs, orientation of fibers, surface treatment of fibers, quantity, direction, and position of fibers (Chung et al., 1998; Ellakwa et al., 2001; Lassila et al., 2002).

Fibers are typically impregnated with resin monomers in order to obtain durable adhesion with the veneering resin composite. Proper impregnation of fibers is significant since fiber reinforcement is only effective when the applied forces could be transferred from the resin matrix to the fibers (Ellakwa et al., 2001). Optimal fiber position and orientation, right positioning of the fiber framework in the bulk of the veneering resin, surface treatment of the pontics, and thickness of veneering material are important aspects that play a crucial role in the stress distribution within the FRC structure (Kallio et al., 2001).

5.1.1 Principles of designing an indirect FRC FDP

The basics of biomechanics and FRC framework design are described in Part I in this book. Indirect FRC FDP could be retained on crowns, inlays, onlays, surface

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bonding wings, or combinations of different retaining elements (hybrid type FRC FDPs). Regardless of the type of the definitive FRC FPD, the load-bearing FRC framework is veneered with laboratory veneering resin composite. The FRC framework and veneering composite allow protection of the FRC from wear and result in a polishable tooth colored surface.

Load-bearing capacity of the FRC FPD is related to the quantity of reinforcing glass fibers, the cross-sectional geometry of the connector, and dimensions of the veneered FDP. Available occlusal space should be minimum as follows:

- occlusal distance between the abutment and the antagonist tooth surface: 2 mm;
- connector: 4 mm;
- occlusal thickness of the pontic: 2 mm.

The quantity of reinforcing fibers is dependent on the FRC product used. In the case of everStick C&B fibers, the recommendation for the minimum number of fibers in the main framework that join the abutments are as follows:

- one replaced tooth in the anterior region: 1 bundle;
- two replaced teeth in the anterior region: 2 bundles;
- one replaced premolar: 2 bundles;
- two replaced premolars: 2–3 bundles;
- one replaced molar: 3 bundles;
- several replaced teeth: 3–4 bundles.

Correct framework design requires also additional fibers to reinforce pontics (see Part I) and in the case of inlay-retained FDPs, an additional surface bonding wing (buccal or palatal/lingual) might be needed when the FDP is retained to the canine or to the tooth with increased mobility. Bonding wing transfers the stress to a wider area in the abutment and lowers the risk for debonding.

Technical steps for fabrication and luting the indirect FRC FDP are as follows (Fig. 5.1):

1. Treatment planning for replacement of acrylic resin partial denture. Preprosthetic occlusal adjustment.
2. Removal of old fillings for inlay retainers or preparation of pillars for crowns.
3. Impression making.
4. Plaster model fabrication and isolation for resin composite application.
5. Planning the fiber orientation and amount of fibers to be used.
6. Adding flowable resin composite to the cavities where the fibers are placed.
7. Placing fibers against the flowable resin composite with transparent silicone package/instrument and initial photo-polymerization.
8. Lamination of adequate number of fibers to the framework by adding flowable resin composite between the fiber bundles.
9. After initial photo-polymerization, removal of the framework from the model and filling the possible gaps with flowable resin composite.
10. Veneering the FRC substructure with laboratory veneering composite.
11. Photo-polymerization in the light-curing oven.
12. Finishing and smooth grinding or grit-blasting of bonding surfaces.

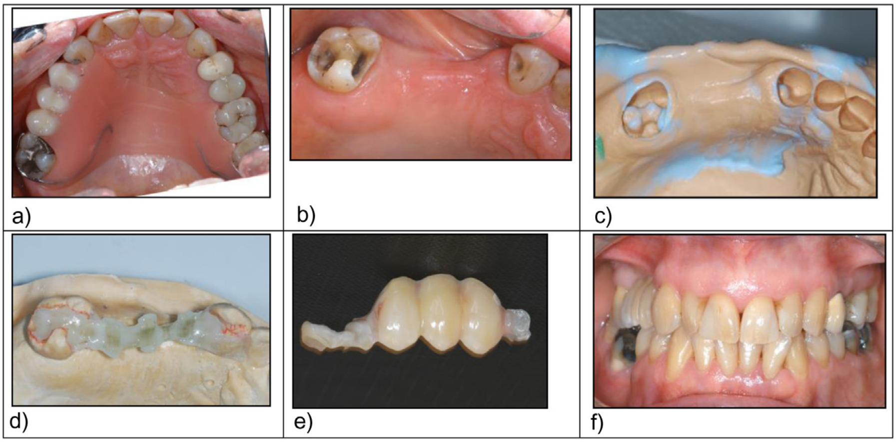

Figure 5.1 (a) Intraoral photo of a patient with missing teeth in the region of 14–16, wearing a removable denture. (b) removal of old fillings and preparing cavities on abutment teeth where the FRC FDP will be bonded. (c) impression making. (d) placement of the FRCs and resin composite that will act as a framework; (e) veneered FRC FDP, (f) inlay-retained FRC FDP luted using a dual-polymerized resin cement.

Steps for cementation:

1. Removal of temporary restorations and cleaning the bonding sites with pumice.
2. Application of photo-polymerized adhesive resin to the bonding surface of the FDP and protecting the adhesive resin from ambient light for 5 minutes.
3. Selective enamel etching and adhesive resin application.
4. Photo-polymerization of the adhesive resin to the bonding site of the FDP.
5. Mixing the dual-polymerized resin luting cement.
6. Luting the FDP, photo-polymerization and finishing cement margins and occlusion.
7. Instructing on cleaning of the reconstructed dentition.

5.1.2 Pontic materials and relevant parameters

FRC FDPs could be fabricated as surface-retained FDPs, inlay-retained FDPs, full coverage crown-retained FDPs and hybrid FDPs (Vallittu and Sevelius, 2000). Inlay-retained FRC FDPs can be made either directly or indirectly. Direct fabrication of FRC FDPs in the mouth requires high clinical skills for establishing a satisfactory anatomical shape of the pontic. Fracture of the pontics or fractures at the connector area are reported as typical complications with FRC FDPs (Vallittu and Sevelius, 2000). In an attempt to overcome such complications, pontics of different materials and designs (Perea et al., 2014a) or improved FRC-resin interfaces (Wolff et al., 2012) have been suggested.

The inclusion of prefabricated pontics in FRC FDPs in particular may simplify the fabrication technique and provide more predictable outcomes for the final FRC FDP. For this purpose, usually acrylic resin-based or porcelain denture teeth are used as pontic materials for direct and indirect FRC FDPs. The use of prefabricated pontics for direct FRC FDPs allows for proper shaping and finishing of the pontic and decreases plaque accumulation and gingival irritation around the pontic compared to directly made resin composite pontics. Prefabricated pontics such as acrylic resin denture teeth have superior mechanical strength and their occlusal adjustment is easier than those of ceramic ones (Powers, 2012). Modern acrylic resin denture teeth provide higher abrasion resistance, improved adhesive properties and enhanced cosmetic-aesthetic values than their older versions (Kawara et al., 1991; Loyaga-Rendon et al., 2007).

In an attempt to improve strength and crazing resistance of resin denture teeth, new technologies have been implemented, some of which are using blend polymers, interpenetrated polymer networks (IPN), and double cross-linking. Denture teeth could also be made of microfilled and nanofilled resin composite which provide optimal optical and mechanical properties. One of the recent generations of denture teeth are made of nano-hybrid resin composite. Such denture teeth are made of a mixture of urethane dimethacrylate resin matrix and poly(methyl methacrylate) (PMMA) clusters that are encapsulated in the structure (Colebeck et al., 2015). Denture teeth of this kind are fabricated in layers that make them not only look more aesthetic but also provide good adhesive properties. Since the outer layer is made of highly cross-linked PMMA, higher cosmetic-aesthetic values and over time higher wear resistance is expected. The ridge-lap surface of denture teeth is less cross-linked and in some denture teeth brands organic and inorganic filler particles are added to this surface (Stober et al., 2006). The less cross-linked layer in the ridge-lap surface promotes better chemical bonding of the acrylic denture teeth to the FRC framework when such teeth are used as pontics in the fabrication of FRC FDPs.

The composition of acrylic resin denture teeth is mainly based on PMMA beads and pigments that are immersed in a cross-linked polymer matrix. The layer between the PMMA beads and the cross-linked polymer matrix is named as semi-interpenetrating polymer network (IPN). In the process of bonding acrylic resin denture teeth to the veneering resin composite, which is the case when such polymeric teeth are used as pontics in the fabrication of FRC FDPs, a chemical mechanism needs to be involved. This is achieved through the formation of a secondary IPN bonding that results after the dissolution of the ridge-lap surface of the acrylic denture tooth by resin monomers. The polymer dissolved by the molecules of the monomer turns into a gel due to the presence of swelling, facilitating the penetration of the monomers (Lastumäki et al., 2002). Consequently, this mechanism enhances the adhesions of the polymeric pontic to the FRC structure in the FDPs.

Acrylic resin denture teeth are in most cases modified at their ridge-lap surfaces when used as pontics in FRC FDPs in order to create a suitable zone for positioning the FRC material. However, this modification may cut off the least cross-linked area of the acrylic resin denture tooth that is in fact crucial in order to achieve good adhesion to the FRC device (Vallittu, 1995). Therefore, acrylic resin denture teeth that are manufactured already with the space could best be incorporated in an FRC framework in direct/indirect FRC FDPs (Fig. 5.2).

Load-bearing capacities and fracture behavior of pre-shaped acrylic resin denture teeth (Perea et al., 2015b) was reported to increase when resin composite was used to fill the space at the bottom of the pontic once the FRC framework was in place.

Figure 5.2 Pre-shaped acrylic resin denture teeth.

The highest load-bearing capacity of 1700 N could be achieved with FRC FDPs especially when pre-shaped acrylic resin denture teeth were filled with short FRCs to complete the ridge-lap shape of the pontics, a magnitude of strength which should be sufficient to withstand the masticatory forces in clinical applications.

As an alternative to acrylic resin denture teeth, ceramic teeth could also be used as pontics in indirectly made FRC FDPs. Recently, computer-aided design/computer-aided manufacturing (CAD/CAM) technologies have been implemented in the fabrication of pontics in order to create proper shapes of pontics that could be adhered to the FRC structure. The acceptance of CAD/CAM manufactured prosthetic solutions is increasing as a consequence of unpredictable results with some traditional methods and the time that they require (Li et al., 2014). Additionally, industrially manufactured blocks are more homogeneous compared to those of the handmade ones, presenting advantages in terms of mechanical properties of the final restoration (Hickel and Manhart, 2001). The inclusion of CAD/CAM manufactured pontic teeth may also overcome some of the shortcomings such as delamination of the veneering material (Göhring et al., 2002), discoloration (Monaco et al., 2003), and wear (Behr et al., 2003). High wear resistance and good aesthetic properties of ceramic might also be beneficial for the provision of long-lasting FRC FDPs with good cosmetic-aesthetic values.

One other important aspect that directly affects the fracture resistance of inlay-retained FRC FDPs is the thickness of the pontic material as in the case of inlay-retained FRC FDPs. It is highly recommended to reinforce the inlay-retained FRC FDPs at the gingival side of the pontic due to the localization of high tensile stress in this area (Dyer et al., 2004; Shi and Fok, 2009). Previous research reports revealed that bending the FRC framework close to the gingiva would increase the biomechanics of the final FRC FDP in that deeper positioning of the FRC framework would also allow for obtaining thicker pontic material above the FRC structure (Özcan et al., 2012; Perea et al., 2014a).

An FRC FDP should withstand the masticatory forces that are reported to be in the range of 150 N for anterior and up to 878 N for posterior teeth (Ahlberg et al., 2003; Ferrario et al., 2004). In a recent study, ceramic pontics of FRC FDPs with 4 mm thick showed mean fracture load values of 1667 N (Perea et al., 2014a) being significantly higher than those with resin composite or acrylic resin denture teeth pontics with similar thickness. However, the values obtained with resin composite and acrylic resin denture teeth pontics also exceeded the values reported for masticatory forces on posterior teeth (Perea et al., 2014a).

Considering that failures primarily occur at the pontic area and connector area, it is crucial to pay attention to the characteristics of the connectors when designing an FRC FDP. One solution to overcome the design problem in this area is to place a similar amount of fibers at the bottom of the pontics and the connectors (Vallittu, 1998). The reason for this is that since in those areas the tensile stress is higher, the fibers would follow the direction of the principal stress. Likewise, additional fiber reinforcement close to the prepared teeth was shown to increase the fracture strength of the FRC FDPs and reduce the incidence of fractures in the crowns (Vallittu, 1998).

5.1.3 Indirect pontic fabrication using CAD/CAM technologies

The use of CAD/CAM technologies has increased over the last three decades due to the introduction of materials that could be used for the fabrication of at the dental office oftentimes in one session (Beuer et al., 2008; Duret et al., 1988). Current CAD/CAM systems consist of a scanner that converts geometry into digital data, a software program to process the data and a production technology that translate the data into the desired product. This technology is applied to design and mill veneers, inlays, onlays, crowns, FDPs, and implant abutments, and is also used for the fabrication of some orthodontic devices. CAD/CAM technologies aim to deliver aesthetic restorations fabricated in an easy, fast, and accurate way, in one session.

Typically, reconstructions using CAD/CAM technologies are from prefabricated blocks of porcelain, resin composite, hybrid of resin composite and/or ceramic, and PMMA after milling procedures (Elsaka, 2015). For ceramic blocks different options are available such as feldspathic blocks, leucite glass ceramic and lithium disilicate ceramic where the latter present higher stability. Glassy matrix ceramics are translucent and therefore more preferable in aesthetically demanding areas in the mouth. Due to the high amount of silica in their composition, such ceramics could be etched with hydrofluoric acid (Sorensen et al., 1991) and thus be inserted on the FRC using adhesive systems.

The process of scanning a preparation includes a gradual movement of the optical scanner on the surfaces of the teeth to be restored as well the neighboring teeth. It is preferable to scan the preparation, interproximal contact areas, the neighboring teeth, and 2–3 mm of gingival tissue on buccal and lingual so that information from all surfaces is available when designing the pontic. The process of scanning an area of a missing tooth for designing a ceramic pontic into an FRC FDP includes similar steps but the FRC framework needs to be in place when scanning. Once the virtual model is generated, it has to be ensured that 100% of the FRC structure, the interproximal contact areas, and at least 90% of the neighboring teeth are present (Fig. 5.3).

When the virtual model meets the requirements and expectations of the clinician, the next steps are similar to the preparation for a single crown. Instead of marking the margins of the preparation, in the case of a pontic of an FRC FDP, the soft tissue of the missing tooth, including the FRC structure, should be marked. CAD/CAM

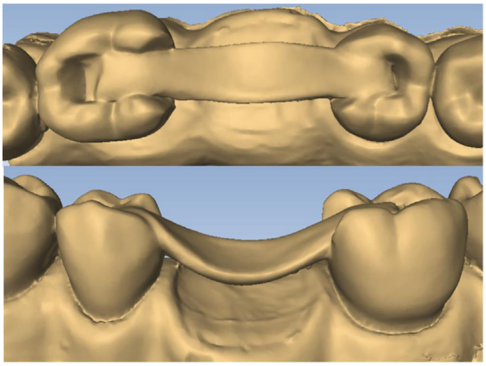

Figure 5.3 Virtual model with the FRC structure in place.

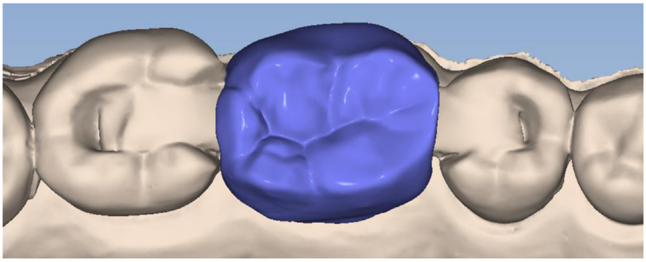

Figure 5.4 Occlusal view of a pontic designed for an FRC structure.

systems also offer selections of tooth anatomy from tooth libraries. The various CAD/CAM systems also offer options to modify the chosen tooth, evaluate the material thickness, and adjust axial walls in addition to many other tools. After the design is accomplished, the pontic for an FRC structure could be viewed from the occlusal (Fig. 5.4) but also it is possible to section the pontic and evaluate the position of the FRC in relation to the overall pontic (Fig. 5.5). Once the proposed pontic is approved, it is ready to be milled for an FRC structure (Figs. 5.6 and 5.7).

Ceramic pontics with 4 mm thickness, measured in cervico-occlusal direction, used in FRC FDPs, have shown high load-bearing capacities with a mean value of 1667 N (Perea et al., 2014a). However, when the vertical space is limited, polymer denture teeth and resin composite pontics could be considered as better alternatives that could also be obtained using CAD/CAM technologies.

5.2 Fiber Framework Design

The FRC framework design is also partially responsible for the durability of FRC FDPs. Typically, failures occur in areas where the fiber framework does not support the veneering material effectively. The fracture pattern is located in many cases between the framework and the veneering resin or within the veneering resin

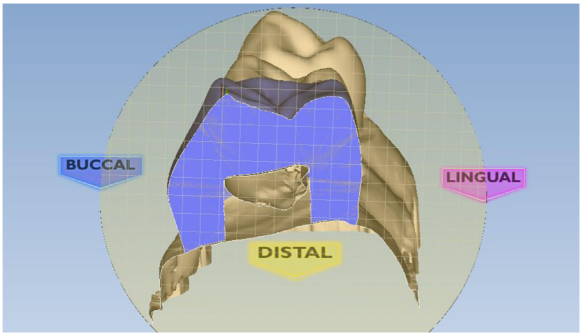

Figure 5.5 Cross-section of the pontic where the position of the fiber could be viewed in relation to the overall pontic material.

Figure 5.6 Milled ceramic pontic from the cervical view with the space for an FRC structure.

material. Thus, FRC frameworks should be designed in such a way that they provide support for the veneering material. Moreover, the FRC framework should also contain sufficient amount of fibers in order to increase the rigidity of the FDP and adhere to the veneering material (Freilich et al., 2002).

Figure 5.7 Final FRC FDP with a ceramic pontic.

A study on the fracture resistance of rectangular, circular, and anatomically-shaped frameworks showed superior performance with circular-shaped frameworks compared with the rectangular-shaped ones (737 N vs 694 N). On the other hand, anatomically-shaped frameworks provided the most favorable fracture resistance (902 N) since this kind of framework design contains more amount of fibers than the other designs (Behr et al., 2005). Another study evaluated the fracture resistance of directly fabricated inlay-retained FRC FDPs with different framework designs. The design that supported the pontic area in the buccolingual direction showed increased load-bearing capacity with a maximum mean load of 2353 N compared to the alternative designs evaluated (Xie et al., 2007). In that study, placing an additional unidirectional FRC on the pontic zone of the main framework provided the support for the pontic.

In a clinical study, FRC FDPs with low-volume framework design, reported veneering resin fractures at an early stage which was then modified and repeated with high-volume design resulting in more support for the veneering composite (Freilich et al., 2002). In another clinical study, the behavior of FRC FDPs with conventional and modified framework designs was compared (Monaco et al., 2003).

The results indicated that the conventional design with a cylindric shape showed higher incidences of fracture failures than the modified design with an oval shape in the pontic area to support the veneering material. In that study, delamination occurred in 16% of the conventional framework designs, whilst 5% of the modified designs showed chipping. These observations support the importance of positioning of the fiber in the framework design.

5.3 Surface Conditioning of Denture Teeth

The strength and longevity of the adhesion to acrylic resin denture teeth depends on the type of bonding surface and denture teeth used (Cunningham, 2000). A variety of bonding mechanisms are available that may contribute to durable connection between the resin-based materials to acrylic resin denture teeth some of which are macro-mechanical retention, micro-mechanical retention, and interpenetrating networks or covalent bonds (Cunningham and Benington, 1999). Some manufacturers and researchers recommend the application of resin monomers in order to pre-condition the surface of the acrylic denture teeth that yield to increase in their adhesive properties. Controversial findings are present regarding the benefits of mechanical retention features placed on the surface of denture teeth (Cunningham and Benington, 1999). The chemical composition of acrylic resin denture teeth facilitates their modification by the use of resin monomers, namely the acrylic surface softens, and resin monomer dissolves into the ridge-lap surfaces.

In the process of chemical surface modification of the polymeric structure of the acrylic resin denture teeth, the polymer is softened by the solvent molecules of the monomer, which allows for the formation of a secondary IPN bonding. The term secondary IPN has been defined to differentiate between semi-IPN structure in the FRC and the one at the network interface between the veneering resin materials and the FRC (Vallittu, 2009). The dissolution gradient depends on different factors such as efficiency of the monomer at swelling and softening the PMMA, wetting time, temperature, and polymeric structure of the substrate (Vallittu et al., 1997). After linear polymers are dissolved, the core of the beads in acrylic resin denture teeth preserves its linear polymeric structure, which then presents suitable bonding sites to adhere this type of teeth to an FRC structure. On the contrary, cross-linked polymers do not dissolve. The contribution of semi-IPN structure for secondary IPN bonding is therefore important when indirect FRC restorations are attached to the tooth substrate and when an old FRC restoration needs to be repaired in the mouth (Wolff et al., 2011).

One study evaluating the influence of different monomers on the ridge-lap surface of these polymeric teeth reported that conditioning systems such as the use of methylmethacrylate 99% (MMA), a flowable resin composite and an adhesive resin consisting of dimethacrylate resin, could increase adhesion to acrylic teeth (Cunningham, 2000; Kawara et al., 1991). Furthermore, increased exposure times of the monomers during wetting the polymeric teeth had a significant impact on adhesion to polymeric teeth surfaces (Perea et al., 2014b). Likewise, the use of resin monomers on the denture tooth surface also affects the surface hardness of the polymeric teeth. The longer the contact time of the resin monomers with the surface is, the less the surface hardness of the polymeric teeth. This could lead to the hypothesis that increased contact time of the resin monomers on the acrylic resin denture teeth surfaces could increase the depth of penetration, which then eventually improves the adhesive properties of polymeric teeth used as pontics in the fabrication of FRC FDPs. Indeed, confocal scanning microscopy evaluations revealed the ability of resin monomers to penetrate the surface of polymeric teeth, supporting this hypothesis (Perea et al., 2015a).

5.4 Concluding Remarks and Future Trends

The main advantage of resin-bonded FDPs over the full-crown retained FDPs is the conservation of dental tissues. In this regard, FRC FDPs not only meet the requirements to be considered as being minimally invasive, tooth-colored reconstructions, but also allow for easy repair in case of failure. The long-term clinical observations on indirect 3-unit anterior FRC FDPs still reveal incidence of fracture of the framework and delamination of the veneering resin composite as the most common reasons of failures (van Heumen et al., 2009). Future study designs could consider the inclusion of a ceramic pontic in 3-unit anterior FRC FDPs as a possible alternative to overcoming the drawbacks mentioned in previous reports. The use of a milled ceramic pontic in 3-unit FRC FDPs using CAD/CAM technologies (Fig. 5.8) may carry some potential for improved aesthetics and longevity, which requires further investigation.

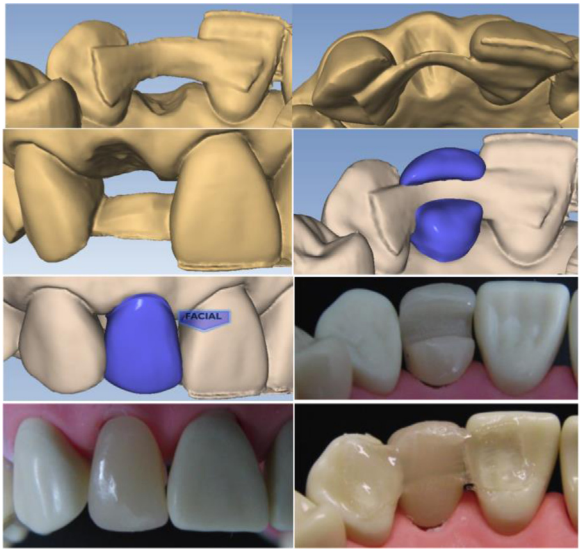

Figure 5.8 Representation of the process of scanning, designing, milling a ceramic pontic and creating a 3-unit FRC FDP.

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Tooth as an adhesive substrate for fiber-reinforced composites

6

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Chapter Outline

6.1 Introduction

In recent decades the quest for durable, aesthetic materials that can restore both function and appearance of lost tooth structure has been the major issue for clinical practice. With the introduction of adhesive technologies, minimally invasive, tooth-colored, adhesive restorations have replaced conventional restorations that sacrificed sound tooth structure for extra retention. However, this approach had limited applications in chair-side replacement of missing teeth due to the shortcomings of the

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available materials. Glass ceramics fulfill the requirements of aesthetics and adhesive properties but lack strength. Zirconia or alumina ceramics or metals have adequate strength but durable adhesion is difficult to achieve. Moreover, none of these materials can be processed directly at the patient's mouth except for some chair-side CAD-CAM materials, which are still expensive. Thus, with the current preimpregnation technologies, fiber-reinforced composites (FRCs) fulfill the gap for direct chair-side applications, both in terms of strength and good aesthetic properties as well as good bonding properties. Continuous FRCs have been shown to possess adequate mechanical properties to function successfully in the oral cavity (Freilich et al., 1998). The light polymerizable resin matrix preimpregnated FRCs can be successfully polymerized with chair-side light curing units (Uctasli et al., 2005). Appropriate selection and arrangement of fibers preimpregnated with light polymerizable resin matrices allows the clinician to exploit the advantageous properties of each material to provide a combination of materials far superior to those otherwise available for direct restoration techniques.

6.2 Adhesion

Adhesion is defined as the mechanism that bonds two materials in intimate contact across an interface (Davidson, 1996). An adhesive is a material that joins two substrates together by solidifying and transferring load from one surface to the other (da Silva et al., 2011). General concepts in adhesive joints indicate that the physicomechanical properties of the adherents and adhesives such as elastic modulus, thermal expansion, and polymerization shrinkage are important for the long-term success of the joints (Ausiello et al., 2002). Adhesively bonded joints are adapted as more reliable alternatives to mechanical joints in many engineering applications and provide many advantages over conventional mechanical fasteners, such as uniform stress distribution along the bonded interface that enables a higher stiffness and load transmission. Due to the polymeric nature of adhesives, adhesive joints provide good damping properties, which also enable high fatigue resistance (da Silva et al., 2011).

In clinical dental applications adhesive technologies also revolutionized the dental treatment strategies. Minimally invasive, tissue saving treatment options can only be achieved when the restorative material integrates well with the hard tissue through effective adhesive procedures that bring both the biomaterial and hard tissue in intimate contact. This results in a complex biomechanical entity, of which the clinical performance is controlled by the quality of the interface between the restorative material and tooth surface (Pashley et al., 2011). Bonding in restorative dentistry is the result of different mechanisms:

1. Mechanical adhesion, penetration of resin to the irregularities on the tooth or restorative materials and interlocking inside these irregularities.
2. Chemical bonding between adhesive and adherent, such as chemical bonding to the inorganic component (hydroxyapatite) or organic components (mainly type I collagen) of the tooth structure.
3. Diffusion adhesion: interlocking between molecules such as the polymer-polymer adhesion through diffusion of polymer chain ends across an interface.

During clinical applications, a combination of these mechanisms are used in situ, within minutes, to achieve a good bonding between restorative materials and tooth structure. The main principles for bonding of FRC restorations to tooth structure follow the same principles as any resin-based direct restoration. While bonding to enamel is reliable through micromechanical retention, bonding to dentin presents challenges due to its more complex collagenous structure. The objective of the current section is to summarize the present knowledge and trends in bonding technologies.

6.3 Tooth as a Bonding Substrate

The tooth is a remarkable natural composite. The brittle, stiff enamel on the outside of the tooth provides wear- and acid-resistance, whereas underlying tough dentin with more flexible structure absorbs chewing stresses and provides structural support for enamel (Nanci, 2012). Although these two natural composites serve successfully in the oral cavity, when replacement is needed, reliable attachment of restorative materials is difficult to achieve due to the large differences between enamel and dentin structure.

6.4 Enamel Adhesion

Enamel is the hardest tissue in the human body, composed of 90 vol% mineral, 4% protein, and 6% water (Nanci, 2012). High mineral content, without any modification, lacks sufficient roughness to allow for the adhesive restorations to adhere to enamel. The ability to bond restorative materials to enamel through surface modification using 85% phosphoric acid for 60 seconds was first introduced in 1955 by Buonocore (1955). Since then, the technique has been modified to reduce the acid concentrations to 32%–37%, as well as etching time to 15 seconds (Legler et al., 1990; Triolo et al., 1993; Barkmeier et al., 2009).

Acid etching of enamel surface cleans the uncut enamel surface by removing organic pellicle, and also cut enamel by removing cutting debris called "the smear layer." Additionally, acid-etching partially dissolves the enamel rods, enhancing the topography of enamel by transforming the smooth enamel surface into an irregular surface with microporosities (Fig. 6.1). It also increases its surface free energy, resulting in the lower contact angle of resins to enamel (Asmussen, 1977; Busscher et al., 1987). When bonding resins are applied to this irregular surface during adhesive procedures, resin penetrates into the surface, aided by capillary action. After polymerization, micromechanically interlocked solid resin tags provide a stable resin-enamel bonding interface. The very low protein and water, as well as the presence of high mineral content in enamel, is the key for reliable adhesion of resin to enamel microporosities (Pashley et al., 2011). Despite the availability of alternative enamel etchants such as maleic acid, citric acid, oxalic acid, phytic acid,

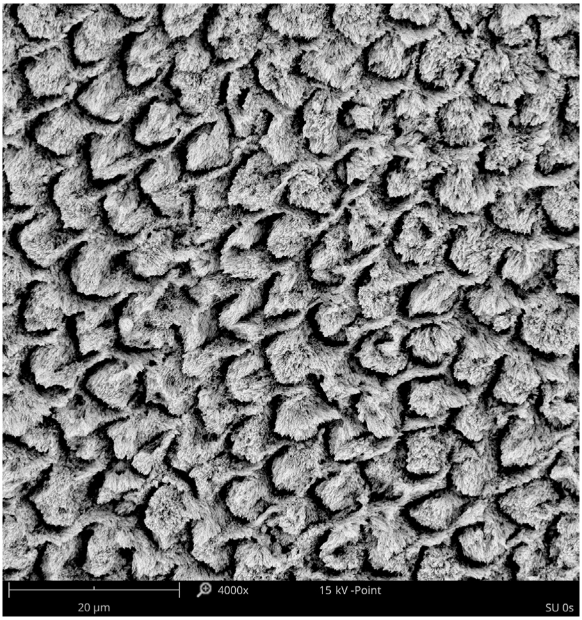

Figure 6.1 Scanning electron micrograph of enamel etched with 37% phosphoric acid for 15 s.

hydrochloric acid, phosphoric acid still remains the etchant of choice with etching time of 15 seconds for both prismatic and aprismatic enamel. This reliable surface bonding is responsible for high laboratory bond strength results (De Munck et al., 2003a,b), as well as minimally invasive restorations lasting more than 20 years (Beier et al., 2012) and protecting the dentin bond against bacterial invasion (De Munck et al., 2003a,b).

6.5 Effect of Enamel Preparation on Bonding

The proper surface conditioning of enamel is important for obtaining sufficient microroughness of the surface. In addition to mechanical roughening through the use of burs, other conditioning techniques include acid-etching, air abrasion, and laser treatment.

6.5.1 *Phosphoric acid treatment*

Even though the bond strength to ground or intact enamel after phosphoric acid-etching is not different, in general the surface aprismatic enamel is more resistant to etching due to the parallel arrangement of the apatite crystallites (Fig. 6.2) that permit a high packing density of the crystallites. This results in a nonuniform

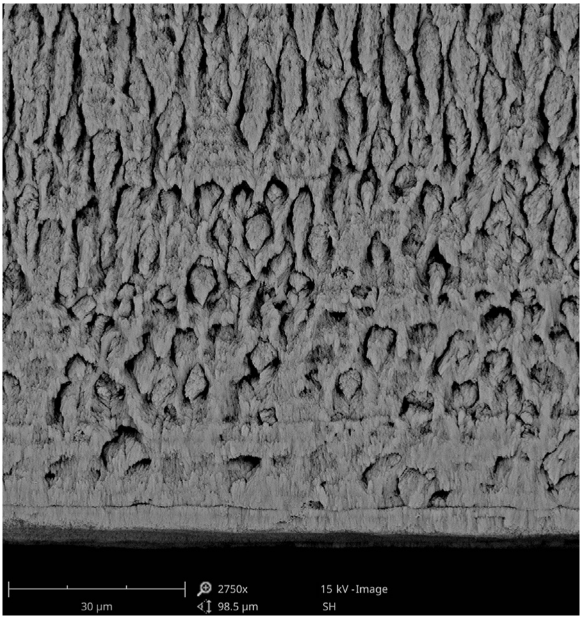

Figure 6.2 Scanning electron micrograph of a horizontal enamel section of a molar tooth treated with 37% phosphoric acid for 15 s. The bottom layer is the aprismatic enamel with very little roughness.

inconsistent etching pattern, showing the remnants of aprismatic enamel with patches of underlying prismatic enamel (Tay et al., 2005). The etching pattern depends on whether the phospohoric acid is applied with (dynamic) or without (static) agitation. Etching without agitation results in the retention of the bulk of aprismatic enamel, and depending on the thickness of the aprismatic enamel layer, only isolated islands of etched aprismatic enamel may appear on the surface. On the other hand, etching with agitation brings fresh acid to the etching front, helps to dislodge loosened etched enamel areas, resulting in a more uniform removal of aprismatic surface layer and also partial exposure of enamel rods of the prismatic enamel.

6.5.2 Air abrasion

Air abrasion, also referred to as sandblasting, is a technique in which a fine stream of particles of aluminum oxide, silica, or baking soda are applied to enamel or other substrates through high pressure causing an increase in roughness of the surface. The main disadvantages of the technique are the removal of the dust particles from the surface. Despite the claims that air abrasion could eliminate the acid-etching, studies evaluating the bond strength to air-abraded enamel showed 50%–60% lower results compared to acid-etching techniques (Charles et al., 2014).

6.5.3 Laser treatment

In recent years there has been a growing interest in the use of lasers for hard tissue conditioning. Laser technology can remove tooth substrate effectively and precisely by means of a thermo-mechanical ablation process involving micro-explosions. Water-cooling is required to prevent cracking and melting of enamel, and to prevent thermal damage to the pulp (Atrill et al., 2004). Studies comparing the Erbium-YAG laser with acid etching showed much lower results (Lupi-Pegurier et al., 2003) whereas some other showed comparable results to acid etching by use of an erbium, chromium, yttrium, scandium, gallium, garnet (Er,Cr:YSGG) hydrokinetic laser system (Uşümez et al., 2002).

6.6 Dentin Adhesion

Adhesion to dentin has been clinically more challenging and less durable due to the intrinsically hydrated and organic nature of dentin (Van Meerbeek et al., 2003, Tezvergil-Mutluay et al., 2015). Structurally dentin is composed of mineral crystals (45−50 vol%) deposited between the network of collagen fibers. Type I collagen is the primary component of the organic matrix (90%), with the rest being other noncollagenous proteins (10%) (Nanci, 2012). Dentin also contains a dense interconnected network of tubules measuring around 1−3 μm in diameter (Fig. 6.3).

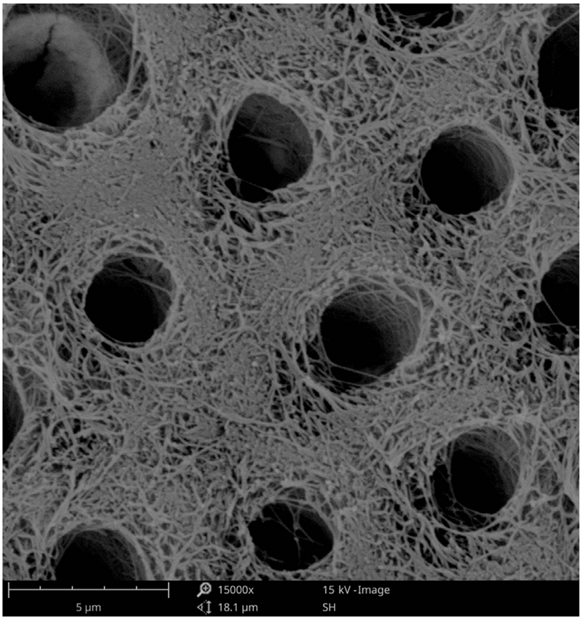

Figure 6.3 Scanning electron micrograph of dentin surface acid etched with 37% phosphoric acid for 15 s followed by rinsing. The intertubular porosity and collagen network serves as a pathway for adhesive resin diffusion.

A hypermineralized dentin sheath called "peritubular dentin" lines the tubules, whereas less mineralized area between the dentinal tubules is called "intertubular dentin." Intertubular dentin contains collagen fibrils with characteristic banding and is mainly available for adhesion. The tubules connect the dental pulp with dentinoenamel junction and both the properties and structural compounds of dentin show high variation with location, resulting in more challenges for bonding procedures (Fig. 6.4) (Nanci, 2012).

Cavity preparation with rotary or hand instruments results in the formation of a loosely attached 1–5 μm thick debris, or "smear layer," on the tooth surface (Gwinnett, 1984). The thickness and morphology of the smear layer probably varies with the dentin surface preparation method and also with the depth of dentin. Smear layer thickness increases with increasing roughness of the diamond bur and a regular grit bur with a grains size of 100 μm creates a smear layer of 2.2. ± 0.5 μm (Tani and Finger, 2002). As the smear layer constitutes an unstable barrier to achieving a good bonding (Fig. 6.5), it can be removed by acid-etching, or it can be made stable by adhesives that can penetrate through the smear layer in order to have a more stable bonding (Pashley and Carvalho, 1997). The conventional adhesion strategy involves etch-and-rinse adhesives, which removes the smear layer and superficial hydroxyapatite through separate etching, and relies on micromechanical interlocking. The second strategy involves self-etch adhesives, which makes the smear layer permeable without removing it. The mechanical interlocking is shallower compared to etch-and-rinse adhesives, and additionally some of them chemically interact with residual hydroxyapatite similar to that of glass ionomers. A third strategy comprises of the materials with inherent capacity to bond to tooth structure, such as self-adhesive luting cements (Van Meerbeek et al., 2003), which will not be covered in this section.

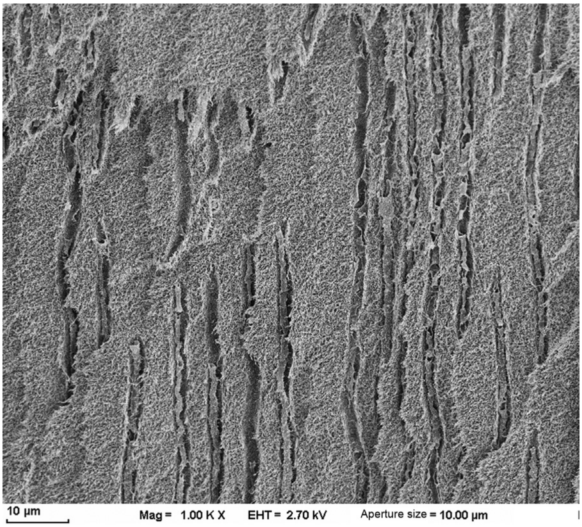

Figure 6.4 Scanning electron micrograph of demineralized dentin that was fractured longitudinally to show dentinal tubules.

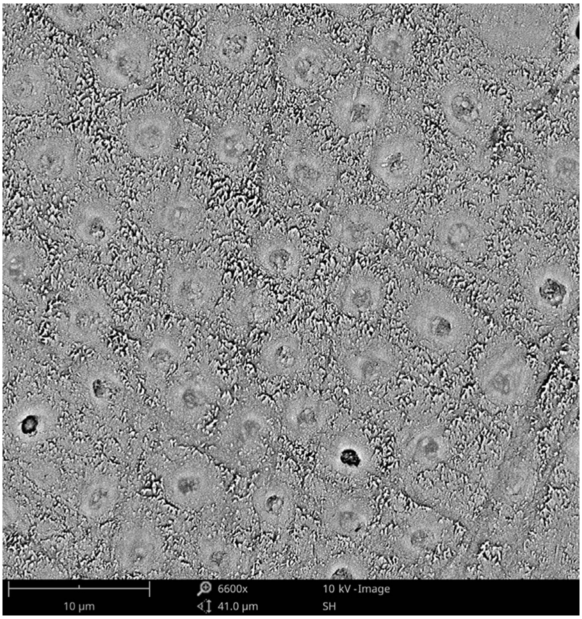

Figure 6.5 Scanning electron micrograph of unetched polished dentin surface with a thin smear layer and dentinal tubules are blocked.

Dentin bonding is also a diffusion-based micromechanical bonding. The mineral content of dentin is solubilized with acid etching and replaced with water, increasing the water content up by to 70% (Pashley et al., 2011), and a mixture of solvents and adhesive monomer are used to displace all that water within 10–20 seconds, and expose the organic matrix of dentin. This is followed by the diffusion of monomers to the demineralized layer, which forms a biocomposite reinforced with collagen fibrils after light polymerization of the resin. This resin-infiltrated biocomposite is called the "hybrid layer" (Nakabayashi et al., 1982), in which the collagen fibrils of the completely demineralized dentin matrix anchor the overlying adhesive resin and tooth-colored resin composites to the underlying mineralized dentin. Proper resin adhesion by encapsulation of collagen fibrils with adhesive resins leads to longer lasting restorations, reduced destruction of dental tissues, and reduced tooth sensitivity. Despite the advent of the contemporary dental adhesives that contain hydrophilic resin monomers to enhance resin coupling to wet dentin, resin-dentin are still imperfect and less durable than resin-enamel bonds over time (Hashimoto et al., 2000, 2003; Pashley et al., 2011; Tezvergil-Mutluay et al., 2015).

6.7 Adhesive Systems

Dental adhesives are classified by their generations, or the number of clinical steps involved. Since classification by generations can be very confusing, a simple and more consistent approach is to classify according to the applied adhesion strategy as etch-rinse and self-etch adhesives (Van Meerbeek et al., 2003).

6.8 Etch-and-Rinse Adhesive System

Etch-and-rinse adhesive systems are the most commonly used systems for bonding and they include either three or two steps of application. Dentin and enamel are treated first with an acidic gel to remove the smear layer and to demineralize the superficial hydroxyapatite crystals, and the remaining acid is rinsed away with water.

6.8.1 Etching step

Both three- and two-step etch-and-rinse adhesives rely on a similar adhesion mechanism. Enamel etching with 32%–37% phosphoric acid dissolves the apatite crystals and creates microporosities, increasing surface area and also surface energy, without any changes at the chemical composition of the surface (Perdigao, 2007; Pashley et al., 2011). In dentin, acid treatment removes the smear layer and demineralizes 5–8 μm of the intertubular dentin surface to expose the underlying collagen fibrillar matrix (Pashley et al., 2011). When drying acid-etched dentin, this collagen network easily collapses and shrinks and adhesive resins can not penetrate thorough this layer to encapsulate the exposed collagen network (Fig. 6.6).

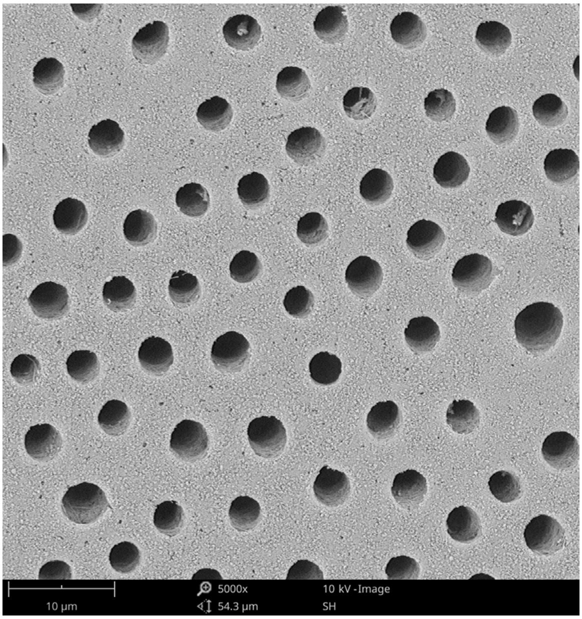

Figure 6.6 Scanning electron micrograph of dentin collagen after acid-etching with 37% phosphoric acid. Dentin was air-dried. The intertubular collagen network porosity was reduced due to the collapsed collagen fibrils.

Therefore, a slightly moist environment was shown to increase the bonding and is defined as wet-bonding technique (Kanca, 1996; Pashley et al., 2011).

6.8.2 Primers

The priming step aims to reinforce the exposed collagen layer after acid etching to create a more reliable link between the dentin and the adhesive layer. Conventional primers in etch-and-rinse adhesive systems consist of polymerizable hydrophilic monomers in an organic solvent such as ethanol or acetone (Vaidyanathan and Vaidyanathan, 2009). They include water and hydroxyethylmethacrylate (HEMA)-rich solutions to ensure the expansion of the demineralized collagen matrix and wet the collagen with hydrophilic monomers. Re-expansion of the collagen matrix that has collapsed upon air-drying after the acid-etching/rinsing step is essential in order to achieve a good bonding (Carvalho et al., 2003). The primer's function is to wet collagen fibril surfaces and to displace water to the full depth of demineralization.

Primers are applied to the surface using a microbrush or similar applicator, agitating the surface slightly according to manufacturers' recommendations. The solvent is an important factor affecting the handling (Tay et al., 1996) and performance (Carvalho et al., 2003) of the adhesives, and requires different amounts of wetness for optimal effectiveness. Water-based adhesives are believed to be the most forgiving regarding applicational errors, such as the degree of dentin wetness or dryness. However, control of moisture may be difficult, e.g., in deep dentin with wide open tubuli (Spencer et al., 2010), and the water remaining in the interface jeopardizes the durability. Ethanol-based adhesives have shown better bond strength when the dentin is mildly wet. Ethanol-based adhesives can re-expand the collagen fibrils better than acetone-based adhesives, but requires significantly longer evaporation times. Therefore, water or water—ethanol based primers require careful evaporation of the solvent (Spencer et al., 2010). Acetone-based adhesives, on the other hand, have water-free formulations, but they have lower hydrogen bonding capacity, thus they are not able to re-expand the collapsed collagen as efficiently as ethanol does. Furthermore, due to the high vapor pressure of acetone, it may evaporate too quickly and may not be able to dehydrate the matrix (Maciel et al., 1996; Pashley et al., 2011).

6.8.3 Adhesive resin

Bonding resins are used between permeable resin primers and the composite restorative material as a hydrophobic barrier. In three-step etch-and-rinse adhesive systems the bonding resin is normally solvent-free, but must contain some hydrophilic monomers to enable good contact and wetting of the primed bonding surface (Pashley et al., 2011). They also contain hydrophobic monomers such as BIS-GMA, TEGDMA (Table 6.1), as well as the photoinitiators. When polymerized, this layer provides a good moisture barrier between the hydrophilic primer layer and hydrophobic composite layer (Pashley et al., 2011). Solvent-free adhesives have water sorption and solubility values that are less than half of that seen for

Table 6.1 Abbreviations of common adhesive monomer used in this chapter

Abbreviation	Chemical name
Bis-GMA	Bisphenol A diglycidyl methacrylate
HEMA	2-hydroxyethylmethacrylate
10-MDP	10-methacryloxydecyl dihydrogen phosphate
4-META	4-methacryloyloxyethyl trimellitate anhydride
Phenyl-P	2-(methacryloyloxyethyl)phenyl hydrogenphosphate
TEGDMA	Triethylene glycol dimethacrylate

two-step etch-and-rinse adhesives (Ito et al., 2005). In two-step etch-and-rinse adhesive systems, primer and adhesive resin are combined into the same liquid that therefore includes also solvated hydrophobic and hydrophilic monomers.

6.8.4 Problems related to etch-and-rinse adhesive systems

Despite the success of etch-and-rinse adhesive systems for enamel bonding, technique sensitivity in dentin bonding and inconsistency in collagen fibril encapsulation through the entire depth of the demineralization zone are common problems related to this approach. As a result, unprotected exposed collagen will be more susceptible to host-derived enzymatic degradation over time. Nevertheless, three-step etch-and-rinse concept adhesives are still today regarded as "gold-standard" and have been shown to work very well with chair-side applications of FRCs (Tezvergil et al., 2003, 2005, 2008).

6.9 Self-Etch Adhesive Systems

Self-etch adhesive systems were developed to reduce the number of application steps in order to have more user-friendly adhesive systems. They are supposed to eliminate the risk of over-etching and over-drying. Self-etch adhesive systems do not require separate acid-etching and rinsing steps, since they are composed of aqueous mixtures of acidic monomers (such as phosphoric acid or carboxylic acid esters) with HEMA and water in the primer formula that simultaneously etch and infiltrate enamel and dentin (van Meerbeek et al., 2003, 2011). As a result, the dissolved smear layer and demineralization products are not rinsed away, but incorporated in the hybrid layers (Tay et al., 2000a,b). Self-etch adhesives can be categorized as two-step or one-step adhesives depending on whether the primer and adhesive resin are provided and applied separately or combined in one single solution.

In two-step self-etching adhesives, the first step includes acidic hydrophilic monomers that etch and prime the exposed collagen network. The second step includes a more hydrophobic adhesive resin. This hydrophobic adhesive resin step makes the interface more hydrophobic and seals the bond more effectively.

In one-step (so-called all-in-one) adhesive systems etching, priming, and resin bonding components are all combined in the same mixture. These could also be divided into two-component and single-component one-step self-etch adhesives. Two component adhesives separate active functional monomers from water, thereby increasing the shelf-life. However, a separate mixing step is needed before application. The single-component one-step adhesive system combine all three steps (etching, priming and adhesive components) in the same mixture and does not require any further mixing (Van Meerbeek et al., 2011).

Water is an essential component of self-etch adhesives as it is needed in the ionization of acidic monomers. Total removal of water from the hybrid layer is unrealistic (Ikeda et al., 2005), raising concerns about the polymerization of the adhesive. This also applies to the high concentrations of solvent that may cause incomplete resin polymerization in case of incomplete evaporation (Cadenaro et al., 2009). The acidity of the self-etch adhesive systems ranges from pH 0.9 to 2.7; the self-etch adhesive systems can be classified as mild ($\text{pH} \geq 2$), moderate ($\text{pH} \approx 1.5$), or strong ($\text{pH} \leq 1$), according to acidity (Van Meerbeek et al., 2011). Therefore, the etching effectiveness and pattern between these products may vary considerably. Strong acidic ones produce typical resin tags at dentin, whereas with the mild ones, dentine is only partially demineralized, leaving a substantial amount of hydroxyapatite crystals around collagen fibrils available for a possible chemical reaction. However, typical resin tag formation cannot be observed. Chemical bonding is mainly related to the presence of specific functional monomers such as 10-MDP, 4-META and phenyl-P (Table 6.1). These monomers contain carboxylic and phosphate groups that are able to ionically bond with calcium in hydroxyapatite. (Yoshida et al., 2000). The use of strong (more acidic) self-etch adhesive is more favorable for the bond to enamel but they underperform in dentin (Shirai et al., 2005). For some mild self-etch adhesive systems, the manufacturers also suggest selective enamel etching with phosphoric acid before the application of the adhesive.

Two-step and some one-step self-etch adhesive systems have relatively higher pH and result in shallower enamel demineralization compared to phosphoric acid. However, either roughening of enamel to remove aprismatic enamel or a separate phosphoric acid enamel etching improves the enamel bonding ability of self-etch adhesives (Frankenberger et al., 2008). While bonding to enamel might be a problem with mild agents, bonding to dentin with two-step self-etch adhesive systems has given results similar to those obtained by the "golden standard" three-step etch-and-rinse adhesives. The actual bonding performance of self-etch adhesives varies significantly depending on the functional monomers they include. Good clinical results for some two-step self-etch adhesives have been reported (Peumans et al., 2005). In general, selective enamel etching followed by the application of a two-step self-etch adhesive has been recommended for the best overall performance of the adhesives (Van Meerbeek et al., 2011). Apart from the pH of the self-etch solution, other factors such as agitation during application, viscosity, thickness of the smear layer, and wetting characteristics affect the resultant depth of demineralization and infiltration by self-etch adhesives (Oliveira et al., 2002).

6.9.1 Problems related to simplified etch-and-rinse and self-etch adhesives

Despite their user-friendliness and low technique sensitivity, simplified adhesive systems (two-step etch-and-rinse and one-step self-etch adhesive systems) have resulted in low bond strength in vitro (De Munck et al., 2006) and less than ideal clinical outcomes. Due to their hydrophilicity, and lack of separate hydrophobic resin coating, cured adhesive layers may act as permeable membranes (Tay et al., 2004), permitting water movement across the adhesive layer when applied on wet dentin. Reticular patterns of nanoleakeage (so-called "water trees") have been found within the adhesive layer of simplified adhesives. They are considered as sites of incomplete water removal and, subsequently, suboptimally polymerized resins, which leads to lower bond strength and less durable bonding.

HEMA-containing formulations are prone to high water sorption, and upon polymerization, HEMA-water mixture forms hydrogel. On the other hand, HEMA-free formulations are prone to phase separations. This can lead to low bond strengths because of the formation of resin globules and poor resin tag formation and often results clinically in postoperative sensitivity. Additionally, the complex mixtures of hydrophilic and hydrophobic monomers and solvents in simplified adhesives, mainly in all-in-one adhesives, make them more technique sensitive. Air-drying is essential in order to remove the water and solvents as much as possible (Hashimoto et al., 2005), but might also result in over-thinning of the adhesive layer at some parts of the cavity, and the pooling of excessive adhesive layer in some other parts. This results in nonuniform adhesive layers, and very thin areas are prone to the lack of polymerization due to the fast oxygen inhibition of thin layers. When restorative material is applied on top of this layer it might displace the adhesive, leaving the composite in direct contact with the hybrid layer. It is important to have a layer of cured adhesive between the restorative material and the hybrid layer in order to avoid the problems associated with thin oxygen-inhibited layers. Another consequence of the complex monomer mixtures is in-the-bottle monomer degradation due to the hydrolysis of the ester groups of the resins (Salz et al., 2005), which limits their shelf-life. To overcome this problem, some manufacturers use two-component one-step adhesives to keep water separated from the functional monomers until the time of application. These products thus require the mixing of two components immediately prior to application (e.g., Adper Prompt L-Pop, 3M ESPE, Futurabond NR, Voco).

6.10 Bonding Properties of Fiber-Reinforced Composites

Bonding properties of resin-impregnated FRCs to dentin or enamel structure is not any different from conventional particulate filler composite systems. During chairside applications, such as fabrication of direct fixed dental prosthesis, direct custom- made fiber posts or periodontal splints, unidirectional continuous or bidirectional weave or short FRCs are adhered directly to the surface of enamel and dentin. The orientation of fibers at the adhesive interface effects the shrinkage behavior, bonding behavior, and also load transfer behavior at the adhesive interface. The anisotropic properties of FRCs results in very low polymerization shrinkage along the fiber direction, and comparable shrinkage to restorative composites transversal to the fiber direction (Tezvergil et al., 2006). These low shrinkage properties were suggested to be an advantage in decreasing the microleakeage and increasing interlocking at the adhesive interfaces (Tezvergil-Mutluay and Vallittu, 2014). Additionally, direct application of FRCs showed better bonding properties, reinforced tooth structure, stopped crack propagation at the interface, and showed lower microleakeage compared to indirect applications (Kumbuloglu et al., 2011; Tezvergil-Mutluay and Vallittu, 2014). For direct chair-side applications, HEMA containing three-step etch-and-rinse adhesives and two-step self-etch adhesives with a nonsolvated resin layer were shown to be reliable options (Tezvergil-Mutluay et al., 2008). The low molecular weight HEMA can penetrate to the linear phases of the semi-IPN matrix of the FRC and thus enhance the bonding.

In addition to unidirectional FRC, both bidirectional and random-oriented FRC bonding properties to enamel and dentin were evaluated (Tezvergil et al., 2005) (Fig. 6.7). However, on enamel surfaces after accelerated aging protocols the bond strength of both bidirectional and random-oriented FRC showed a higher decrease in bond strength compared to unidirectional FRC (Tezvergil et al., 2003, 2005). The thermal expansion coefficient of bidirectional and random-oriented FRC is much higher than the unidirectional FRC along the fiber direction.

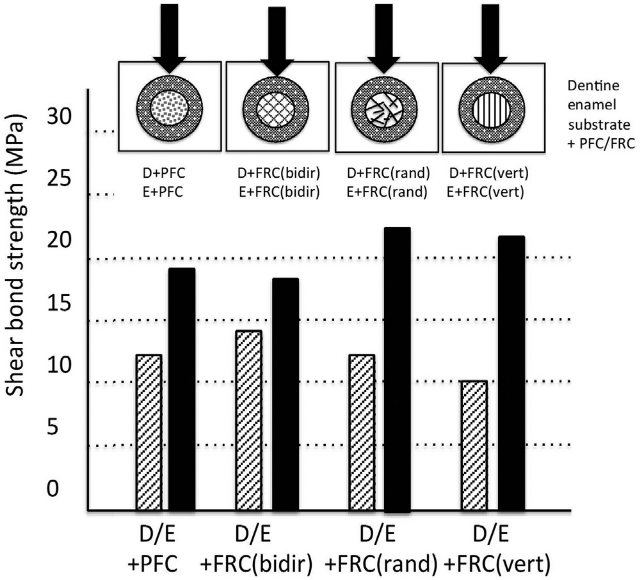

Figure 6.7 Shear bond strength (MPa) of fiber-reinforced composite with different orientations (FRC(bidir) = bidirectional fibers, FRC (rand) = randomly oriented fibers, RC(vert) = vertical unidirectional fibers) to dentin (D) and enamel (E). (Tezvergil et al., 2003, 2005).

6.11 Clinical Recommendations

For direct chair-side applications of FRC, bonding to enamel is still best accomplished using the etch-and-rinse approach. The in situ polymerization of adhesive resins in the etched pits creates a durable micromechanical interlocking and also good diffusion to FRC framework. The enamel bond not only effectively seals the restoration margin but also protects the vulnerable dentine bond against degradation. Bonds formed to enamel with etch-and-rinse systems are strong and durable because their ability to wet and impregnate etched enamel is efficient.

When FRC is applied directly on dentin structure both three-step etch-and-rinse adhesive systems and mild two-step self-etch adhesive systems with a separate adhesive layer application show a clinically reliable bonding between FRC and dentin. The use of one-step (all-in-one) self-etch systems cannot be recommended for chair-side applications of FRC. One-step (all-in-one) self-etch adhesive systems often show an inefficient clinical performance.

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Root canal anchoring systems

7

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Chapter Outline

7.1 Introduction: Key Requirements

Endodontically treated teeth with a substantial coronal loss of dentin may require additional support to retain the coronal restoration. The use of posts has decreased along with the development of adhesive techniques and materials. Yet, when remaining coronal tissue is scarce, additional bonding surface, retention, and support from the root canal is needed especially in anterior teeth and premolars.

In conventional fixed prosthodontics the role of root canal posts is closely related to the selection of materials, i.e., the use of metal posts and porcelain-fused-to-metal crowns. A root canal post provides retention to the crown against vertical debonding forces. Resistance against the lateral and oblique bending forces is obtained by constructing the crown with a circumferential metal ferrule around the remaining dentine. Ferrule of the width of 1.5–2.0 mm alters the stress distribution in the postcore-tooth system and lowers risk for root fractures caused by metal posts that have a high modulus of elasticity and structural stiffness. The use of long metal posts instead of short ones also reduces the magnitude of stresses that can cause root fractures. The paradigm shift in material selection and treatment concept, from metals to ceramics and resin composites, and from mechanical retention to adhesively retained constructions, has also considerably changed the concept of the

Clinical Guide to Principles of Fiber-Reinforced Composites in Dentistry.
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post-and-core system. With nonmetallic crown materials, the function of the ferrule has become less important, whereas the function and properties of root canal posts and adhesive systems is emphasized. Load from the occlusal surface is transmitted to the root and periodontal tissues by adhesive interfaces of restorative materials including the root canal post. Adhesion of root canal posts is based on adhesion of luting cement to dentine and to the post surface. Principles in adhesion of resins to fiber-reinforced composite (FRC) materials are described in Chapter 3, Structural properties of dental FRC structures of this book, and dentine and enamel bonding in Chapter 5, Fabrication of direct dental FRC devices.

7.2 Prefabricated FRC Posts

FRC root canal posts were introduced in the early 1990s. Ever since, they have gradually gained popularity over traditional metal posts in anchoring cores and crowns to the root (Mannocci et al., 2005; Qualthrough et al., 2003). The basic structure and mechanical properties of FRC materials and root canal posts are described in Chapter 3, Structural properties of dental FRC structures. FRCs offer several benefits in restoring endodontically treated teeth. Modulus of elasticity close to that of natural dentin, high tensile strength, and the suitability for cost-effective chair-side techniques make FRCs well suited to the restoration of structurally compromised endodontically treated teeth. Unidirectional FRC can be used both as prefabricated fully polymerized solid posts and as individually formed in situ polymerized posts. The majority of prefabricated posts have highly cross-linked polymer matrices between the reinforcing fibers. This type of matrix polymer does not enable a durable bond between the resin based luting cement or core-build-up resin composite and the post (Rasimick et al., 2010;Kallio et al., 2001). When the posts contain a semi-IPN polymer structure (Chapter 3: Structural properties of dental FRC structures), a durable bond between the post and resin composite is achieved (Fig. 7.1).

There are many suggested advantages in using prefabricated FRC posts, compared to conventional metallic posts. One of the most important benefits of glass FRC is the suitable elastic modulus, which should result in fewer root fractures and fewer unfavorable failures (Fokkinga et al., 2004). Additional advantages of prefabricated FRC posts are good esthetics and the ease of build-up and removal in situ. However, as clinical experience and research data on prefabricated FRC posts increases, we have come to learn about their shortcomings as well. The predetermined shape and diameter of a prefabricated FRC post seldom follows the anatomy of the root canal. Therefore, when placing a prefabricated FRC post, a large space will be filled with resin cement coronally and an unnecessary amount of dentin may have to be removed apically. To avoid unnecessary preparation, a post with a smaller diameter is often chosen, resulting in a postcore structure with an inadequate stiffness and load-bearing capacity.

The failure mechanisms of teeth restored with prefabricated FRC posts have recently been discussed in the literature. Publications address the technique sensitivity and possible incorrect indications in the use of prefabricated FRC posts (Lancaster, 2015; Barfeie et al., 2015; Vallittu, 2016). Failures of root canal post

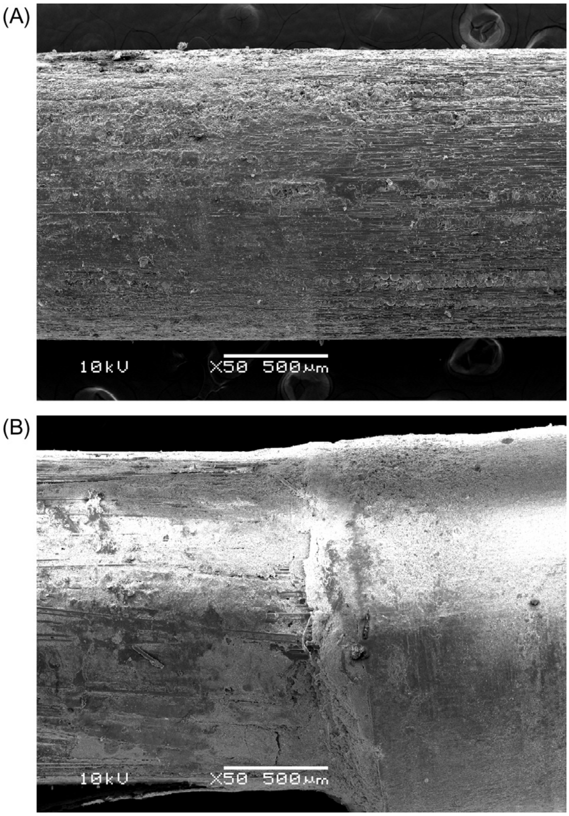

Figure 7.1 SEM micrographs of the surface of cross-linked FRC post (A) and semi-IPN FRC post (B) after pull-out test (resin composite luting cement was debonded from the post). Luting cement is left on the semi-IPN post showing good bonding of the cement to the post (original magnification × 50, bar = 500 μm).

retained crowns relate typically to the use of thin prefabricated root canal post in heavily loaded teeth. Adhesion of resin composites to root dentine may fail in time, which leads to marginal breakdown and secondary caries (Schmitter et al., 2011). This problem is emphasized when the restoration is lacking an outer ferrule (Naumann et al., 2006). A prefabricated root canal post placed to the center of the root canal can provide very little mechanical support to resist damaging stresses on the margins of the crown. This will lead to the catastrophic failure of the crown-tooth systems, with the following stages: (1) Marginal breakdown due to inadequate bonding to dentine; (2) Interfacial fracture propagation due to inadequate support by the post in the center of the root canal; (3) Delamination of resin composite cement from the post due to poor bonding properties of cross-linked posts; (4) Delamination of the FRC post itself due to bending which exceeds the limit of plastic deformation of FRC post (Fig. 7.2). Fig. 7.3 shows severely damaged restoration which had been supported by prefabricated cross-linked FRC post.

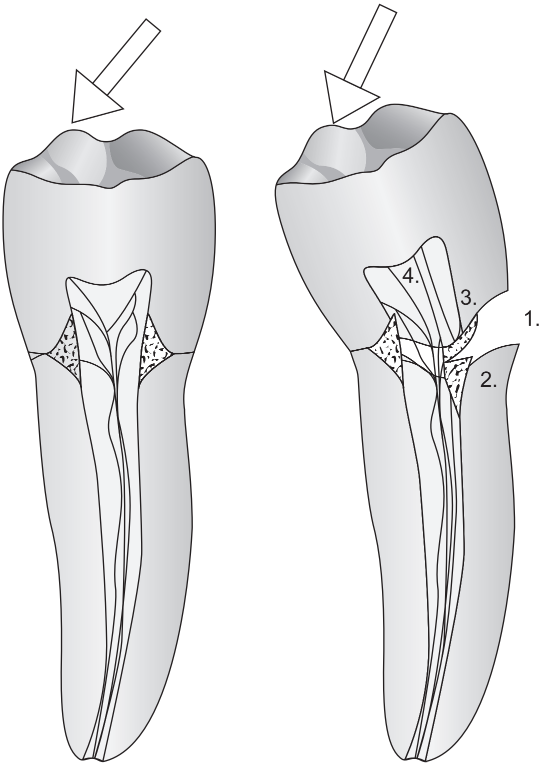

Figure 7.2 Stages of failure of crown-tooth system when prefabricated cross-linked polymer matric FRC post is used.
Modified from Vallittu, P., 2016. Are we misusing fiber posts? Guest editorial, Dent. Mater. 32, 125−126.

Figure 7.3 Maxillary canine has been restored with a prefabricated cross-linked polymer matrix FRC post to support the crown. Three years after placement of the restoration, delamination of composite core and of post itself has occurred and the remaining root is severely affected by caries.

7.3 Individually Formed FRC Posts

Attempts to eliminate the disadvantages of prefabricated FRC posts have given rise to new alternatives on how to restore root canal treated teeth with a post in an optimal way. Greater resistance under loading and more favorable fractures were reported with individual customized FRC posts compared to prefabricated FRC posts (Corsalini et al., 2007). Significantly higher bond strength and fatigue resistance has been reported with individually formed glass FRC posts compared to prefabricated posts (Qualthrough and Mannocci, 2003; Lassila et al., 2004; Le Bell et al., 2004, 2005; Bitter et al., 2007). Fig. 7.4 presents a clinical case where endodontically treated premolars are restored using individually formed posts and cores to build up the coronal dentin and to retain full-cover ceramic crowns.

An individually formed FRC post with a semi-interpenetrating polymer network (IPN) polymer matrix is made from nonpolymerized fiber-resin prepregs, consisting of glass fibers and light-curing resin matrix. The purpose of the individual or custom-made FRC post is to fill the entire space of the root canal in cross-section with the FRC material, following the anatomical form and using minimally invasive preparation (Fig. 7.5). This way, more reinforcing fibers may be placed in the cervical parts of the canal where high tensile stresses occur, resulting in increased resistance (Bitter et al., 2007; Le Bell-Rönnlöf et al., 2011). The increased fiber quantity

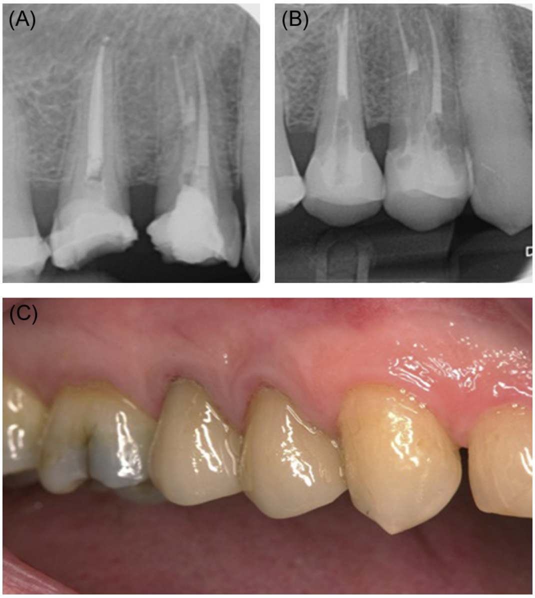

Figure 7.4 Maxillary premolars have received endodontic therapy (A). The coronal dentin is restored with post and core buildups using individually formed FRC posts and composite resin. The treatment is finalized with full-cover crowns made of lithiumdisilicate reinforced glass ceramic, as seen in the radiographic image (B) and clinical picture (C).

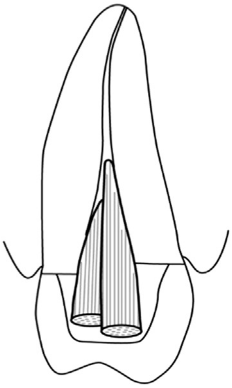

Figure 7.5 Schematic representation of an endodontically treated tooth restored with a direct post and core restoration using an individually formed FRC post. Fiber volume is increased in the coronal part of canal offering structural stiffness and optimal placement of reinforcing fibers, a so-called "inner-ferrule effect" (Tanner and Le Bell-Rönnlöf, 2016)

in the coronal part of the root canal increases the load-bearing capacity of the post system. A FRC post formed with this technique resembles the design of a traditional cast post and core. With gradual apico-coronal increase in thickness, following the anatomy of a modern flared canal preparation, more dentin can be saved in a structurally compromised tooth.

Additional benefits of the individual technique emerge from bonding properties. With the individually formed FRC post, which consists of a semi-IPN polymer matrix between the fibers, problems concerning the adhesion between post and resin luting cements as well as composite core materials are minimized. The bond between individually formed FRC posts and resin cements has been reported to be good (Le Bell et al., 2004, 2005; Mannocci et al., 2005; Bitter et al., 2007). When post dimensions closely follow the dimensions of the canal orifice, the cement thickness can be reduced. This is well demonstrated by the radiograph in Fig. 7.4B. This lowers to some extent the polymerization contraction stress in the adhesive layers between the post and the surrounding dentin.

The biomechanics of the tooth is better simulated by placing the fibers closer to the dentinal wall, where the highest stresses occur (Guzy and Nicholls, 1979; Torbjörner, 2000; Hatta et al., 2011). When the outer ferrule of the restoration is lacking, adhesive failure and marginal leakage, especially on the tension side of the tooth, is a common failure type seen in teeth restored with prefabricated FRC posts (Schmitter et al., 2011). The individual FRC post approach aims to diminish the adhesive failures of the restoration by providing increased structural stiffness and resistance in the critical cervical area. Moreover, a tooth restored with a short and thick individual FRC post has been reported to withstand higher loads than a tooth restored with a thin and long individual FRC post (Hatta et al., 2011). This technique offers benefits also from an operative perspective. A shorter root canal preparation is less time-consuming and unnecessary hard-tissue removal can be avoided.

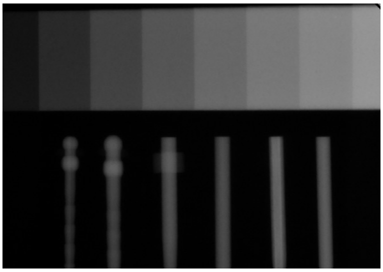

Figure 7.6 Aluminum step wedge from 1 mm to 8 mm thickness is used as reference for determining radiopacity of polymer based restorative materials (ISO International Standard 4049, 2009). X-ray shows radiopacity of prefabricated FRC root-canal posts (from the left: ParaPost Fibre Lux (Coltene/Whaledent); ParaPost Fibre White (Coltene/Whaledent); RelyX Fibre Post (3M Espe); Fibre Post (GC Corporation); Rebilda Post (Voco); FRC Postec Plus (Ivoclar/Vivadent)).

7.4 Radiopacity of FRC Posts

Root canal posts, like other restorative materials, should be visible in radiographic examination, which includes conventional x-rays and panoramic tomograms and novel cone-beam computer tomograms. Dental restorative resin composites have been modified to have adequate radiopacity by using filler particles which contain elements of radiopacity, such as zirconium. International standard (ISO International Standard 4049, 2009) places limits on the minimal radiopacity of polymer based restorative materials as tested by regular x-ray apparatus and aluminum step wedge.

FRCs vary in terms of radiopacity: lowest radiopacity is found with carbon/graphite fibers and polyethylene fibers. E-glass FRC is having radiopacity comparable to that of compact bone and dentin, which is not satisfactory for good visibility in x-rays. Modification of FRC materials by including radiopaque filler particles in the composite lowers the quantity of reinforcing fibers and thus the strength and modulus of elasticity of FRC post. Therefore, other methods beside the adding of minor quantities of radiopaque filler have been used to achieve sufficient visibility in x-rays (Fig. 7.6). Visibility of FRC posts can also be obtained by using radiopaque resin luting cements. These methods include compositional changes of the glass fibers. Also modifications of the resin matrix have been suggested (He et al., 2012). On the other hand, minor radiopacity is beneficial to elimination of artifacts in cone-beam computer tomography imaging, which is not the case with zirconia or metal root canal posts (Fig. 7.7) (Kuusisto et al., 2015).

7.5 Thick or Thin Post and Long or Short Post?

The recommended preparation length for posts has been changing since the use of more flexible post materials has become increasingly common. Traditional rigid metal posts require a long post preparation in order to reduce the stress and the risk

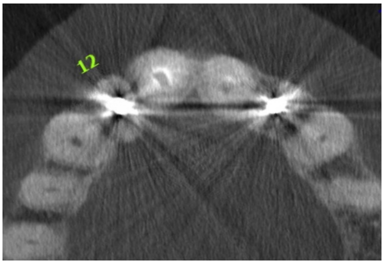

Figure 7.7 Cone-beam computer tomography of cross-sections of lateral upper anterior incisors with gold alloy root canal posts which cause severe artifacts and harm diagnostics of root fractures and periapical infections. Central incisors have been treated with individual FRC posts and no artifacts are caused.

of root fracture (Shillingburg et al., 1970). For flexible prefabricated FRC posts a preparation length of approximately half the root length has been stated to be sufficient to promote adequate mechanical strength for the post restoration (Cecchin et al., 2010). Also, it has been reported that teeth restored with prefabricated FRC posts with a length similar to the length of the clinical crown yield adequate fracture resistance (Adanir and Belli, 2008). Shorter post preparation depth is preferable and is, especially from a clinical perspective, beneficial since it is easier, less time-consuming, and prevents the weakened root from unnecessary preparation.

In the case of individual FRC posts with a semi-IPN polymer matrix that provides successful bonding to resin cements and composite cores and a possibility to place the fiber reinforcement correctly, the adequate post length could even be shorter than the length of the clinical crown (Hatta et al., 2011).

A common problem with prefabricated FRC posts is that in order to save dentin, posts that are too thin are often used. In these cases the fiber reinforcement is placed in the neutral axis of the root canal where no stress exists and the post reinforcement is therefore useless. If the restoration is lacking an outer ferrule, the post restoration will not provide mechanical support and stability and will eventually fail in terms of adhesive failure and marginal leakage (Fig. 7.2). The correct placement of the fiber reinforcement is at the outer surfaces of the root canal and a high volume of fibers is especially needed at the cervical area. This is very seldom achieved with a prefabricated FRC post (Fig. 7.8A). With an individually formed FRC post on the other hand it is possible to design and place a high volume of fiber bundles close to the dentinal walls at the cervical/coronal area where the highest stresses are located (Fig. 7.8B). Hatta et al. (2011) reported that a tooth restored with a thick and short individual FRC post resisted higher loads than a tooth restored with a thin and long individual post. In conclusion it seems that to date a thick and short individually formed FRC post would be a biomechanically optimal alternative. A semi-IPN post can be light-cured directly to the root canal simultaneously with the dual curing of resin luting cement. Glass fibers of the post transmit the curing light and polymerize the resin matrix of the post (Fig. 7.9).

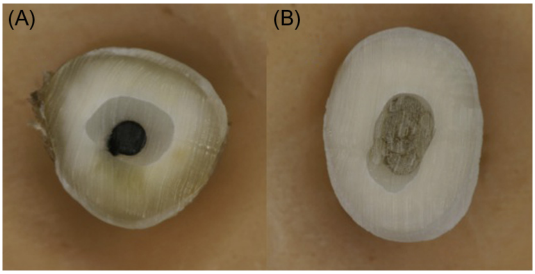

Figure 7.8 Endodontically treated teeth are restored with a prefabricated carbon/graphite fiber post (A) and an individually formed FRC post (B). Teeth were cut cross-sectional at gingival margin level. In a coronally flared root canal the individual post technique offers efficient and precise use of reinforcement, compared to a standard prefabricated post technique.

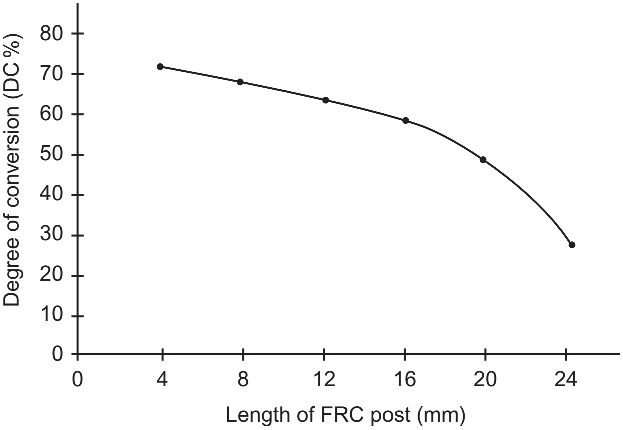

Figure 7.9 Diagram which shows polymerization (DC%) of light curing resin matrix of semi-IPN fiber post. Adequate curing by 40 s light curing can be obtained to the depth of c.16 mm. Modified from Le Bell, A.-M., Tanner, J., Lassila, L.V.J., Kangasniemi, I., Vallittu, P.K., 2003. Depth of light-initiated polymerization of glass fiber-reinforced composite in a simulated root canal, Int. J. Prosthodont. 16, 403–408.

7.6 How to Make an Individually Formed FRC Post: A Step-by-Step Clinical Protocol (Semi-IPN Post Material: EverStick Post, Stick Tech-GC), Illustration of the Procedure is Seen in Fig. 7.10A–J.

- Isolate the area with rubber-dam
- Remove old fillings when necessary
- Remove root canal obturation material with a rotating instrument using a slow speed handpiece (e.g., gates glidden bur) Fig. 7.10A

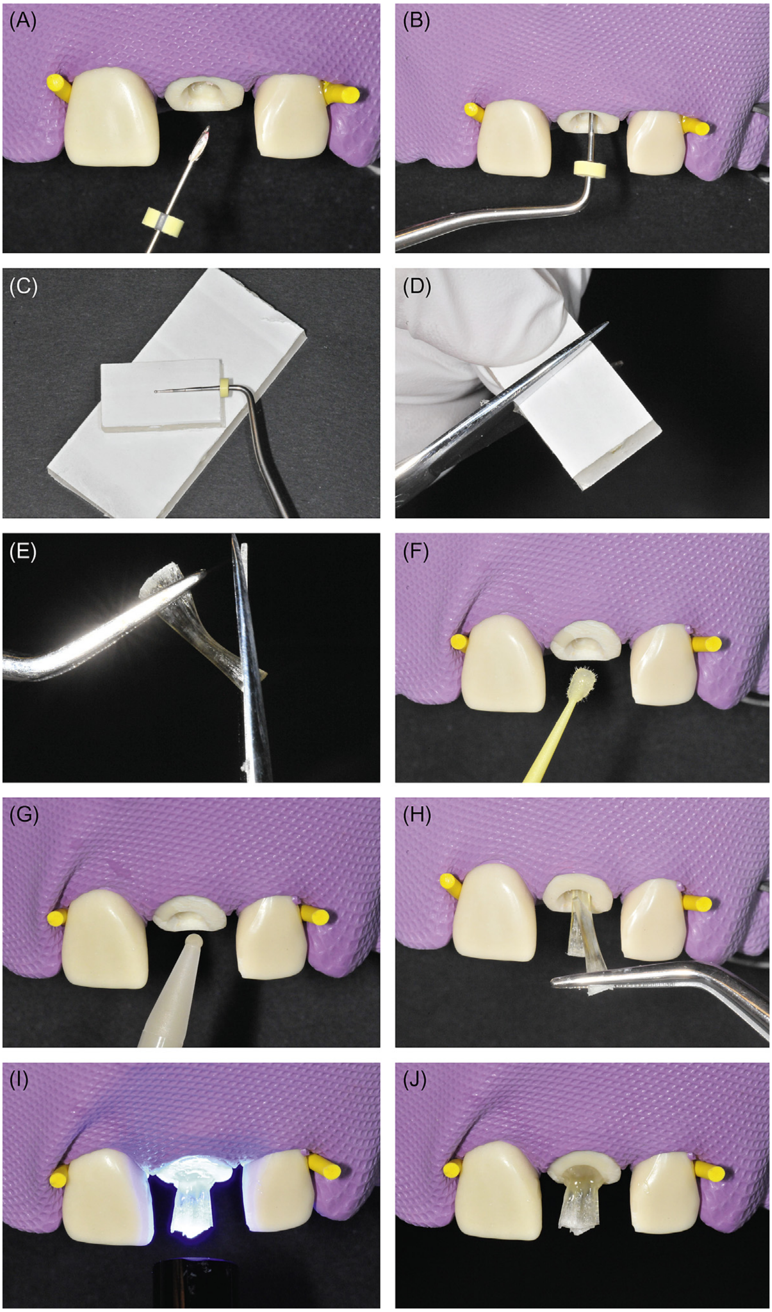

Figure 7.10 (A–J): Step-by-step illustration of making an individually formed root canal post.

  - The length of the root canal preparation should equal the height of future clinical crown
- Rinse with NaOCl followed by distilled water and dry with air (Bitter, 2016)
- Measure canal depth and add coronal dentin height = length of fiber needed Fig. 7.10B
- Cut the measured amount of the fiber post material with sharp scissors Fig. 7.10C and D
- Use two sets of tweezers to flare the coronal end of fiber bundle and make an oblique cut at the apical tip of fiber bundle thus easing the placement into the canal Fig. 7.10E
- Pretreat the root canal and coronal dentin according to the cement you are using Fig. 7.10F
- Apply a small amount of cement into the canal (use a flowable, dual cured resin cement) Fig. 7.10G
- Place the fiber bundle into the root canal, control seating depth Fig. 7.10H
  - Use a hand instrument (e.g., carver) to make room for the second, lateral fiber bundle
  - Cut a second, shorter piece of the fiber and place it into the canal
  - When needed, use more fibers to fill the entire coronal opening of the root canal, repeating the previous steps
- Remove excess cement and light cure for 40 seconds Fig. 7.10I
- Continue with core build-up or composite resin restoration Fig. 7.10J

7.7 Summary: What Can We Learn?

Restoration of nonvital teeth has advanced towards biomechanically driven concepts, conservation of tissue, and adhesion being the most relevant elements for improved long-term success (Dietschi et al., 2008). FRCs and especially their direct chair-side applications are a pertinent part of the evolution, and support this contemporary treatment approach. Common failures of FRC postcore systems are related to the use of thin, weak posts in heavily loaded teeth. Customized, chair-side fabricated fiber-reinforced posts and restorations offer additional benefits over prefabricated standard posts. These include a tailored load-bearing capacity and improved bond strength in adhesive interfaces.

7.8 Future Trends

Root canal anchoring will remain as an important tool in restorative and/or prosthetic treatment. Understanding the biomechanics and principles of creating durable long-term adhesive interfaces to root canal dentine and root canal posts will enhance prognosis of the root canal treated tooth with a crown restoration. Knowledge of wider and less deep root canal post systems, i.e., individually formed posts, has already now changed the treatment concept of FRC posts. On the other hand, the encouraging clinical outcome of root canal treated teeth with so-called endocrowns, i.e., crown and large onlays without postcore system but with a box-preparation and corresponding extrusion of the crown or onlay, reflects a decrease in the need for posts, especially in molars.

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Periodontal and trauma splints using fiber reinforced resin composites

8

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Chapter Outline

8.1 Introduction—What Is Splinting?

A splint is defined as "a rigid or flexible device that maintains in position a displaced or movable part; also used to keep in place and protect an injured part". A secondary definition of a splint is "a rigid or flexible material used to protect, immobilize, or restrict motion in a part" (Van Blarcom, 1999). The two main objectives of splinting in a patient where tooth mobility is normal or at least no longer increasing (Friskopp and Blomlof, 1984) and the patient is able to function comfortably (Vogel and Deasy, 1977).

8.1.1 Periodontal splinting

Periodontal disease is considered as an infectious pathology caused by the interaction between a susceptible host and bacterial factors present in dental

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plaque (Davies et al., 2001; Forabosco et al., 2006). Inflammatory process yields to disorganization of periodontal fibers, induction of bone resorption and eventually destruction of epithelial cell attachment (Davies et al., 2001; Hallmon and Harrel, 2004; Ramfjord and Ash, 1981). As a consequence, teeth drift, diastema takes place between teeth, gingival margins recede, dark roots get exposed, interdental tissue shrinks, and black triangles form in the embrasure spaces (Hellsing, 1980; Oosterwyck et al., 2003; Serio, 1999). Such dental and gingival alterations tend to persist even after healing from the disease, with major social and psychological implications for the patient and a negative impact on the strive to maintain optimal oral health (Bernal et al., 2002; Judge et al., 2003).

Treatment of tooth mobility in periodontal disease is determined by the degree of damage to the bone support. For mobility caused by a widened periodontal space as a result of adaptation to functional demands (Bernal et al., 2002; Davies, 2001; Serio and Hawley, 1999), the treatment is usually occlusal adjustments in combination with periodontal therapy (Bernal et al., 2002; Davies et al., 2001). In teeth affected by gingival inflammation and with higher mobility due to loss of bone tissue (Davies et al., 2001; Serio and Hawley, 1999), the treatment modality is a combination of periodontal therapy, occlusal adjustments, and tooth splinting for stability (Bernal et al., 2002; Forabosco et al., 2006; Ramfjord and Ash, 1981; Serio and Hawley, 1999; Sewón et al., 2000). Periodontal splinting redistributes functional and parafunctional forces (Serio, 1999) and this helps the process of reorganization of the gingival tissues, periodontal fibers, and alveolar bone (Ramfjord and Ash, 1981), and thereby maintains patient comfort (Forabosco et al., 2006; Hallmon and Harrel, 2004; Ramfjord and Ash, 1981). When periodontal splinting is performed before surgical periodontal therapy, tooth stabilization and tissue healing could be promoted by reducing inflammation (Forabosco et al., 2006; Serio, 1999) (Fig. 8.1).

In the past, splinting periodontally mobile teeth was recommended based on the assumption that tooth stabilization had a direct impact on the periodontal healing and gain in attachment (Fleszar et al., 1980; Kegel et al., 1979). Recently, a number of studies investigated these assumptions and found lack of correlation between teeth mobility and periodontal disease healing (Bhaskar and Orban, 1955; Ericsson et al., 1984; Glickman et al., 1966; Glickman, 1963; Lindhe and Ericsson,

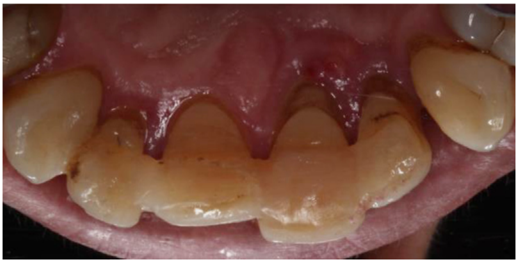

Figure 8.1 An example of direct FRC splint fixing the periodontally mobile maxillary anterior teeth.

1976; Poison, 1983). However, even if teeth mobility is not a causative factor for periodontal disease, teeth stabilization of periodontally mobile teeth is indicated for effective occlusal treatment and prevention of secondary occlusal trauma or injury resulting from normal occlusal forces applied to teeth with inadequate periodontal support (Glickman and Smulow, 1965, 1967; Page et al., 1997; Polson, 1986; Spear, 1997). Recent in vivo studies show that secondary trauma from occlusion is a frequent finding in periodontal patients and its quantity and quality is positively correlated with the extent and severity of the disease (Bernhardt et al., 2006; Branschofsky et al., 2011; Harrel and Nunn, 2009; Nunn and Harrel, 2001). Teeth splinting in periodontal patients is also indicated when teeth mobility becomes a functional limitation and interferes with eating and speaking. Teeth mobility can be very distressing for the periodontal patient and is often referred as a chief complaint (Kumbuloglu et al., 2008, 2011). Although successful treatment of the inflammation can result in decrease of teeth mobility, this can never be complete in the case of severe bone loss. In such cases, teeth splinting is the only way to completely stabilize the teeth and allow comfortable function for the periodontal patient (Bernal et al., 2002; Mosedale, 2007; Strassler, 2009; Tarnow and Fletcher, 1986) (Fig. 8.2A and B).

In addition to periodontal diseases, occlusal forces also play an important role on tooth mobility as they may exacerbate a preexisting periodontal lesion when they exceed the resistance threshold of a compromised attachment apparatus (Davies et al., 2001; Forabosco et al., 2006; Hallmon and Harrel, 2004; Ramfjord and Ash, 1981; Serio and Hawley, 1999). In the presence of frequent loading, the time required for bone remodeling may not be sufficient, and this causes bone resorption (Serio, 1999). Reduced periodontal attachment can therefore result in tooth mobility and migration, causing misaligned occlusal forces that hinder the balance between bone resorption and bone remodeling (Oosterwyck, 2003) and the reorganization of periodontal fibers (Serio and Hawley, 1999). The relationship between occlusal trauma and tooth mobility therefore depends on the intensity and frequency of occlusal forces (Bernal et al., 2002; Davies et al., 2001; Forabosco et al., 2006; Gibbs et al., 2002; Hallmon and Harrel, 2004; Ramfjord and

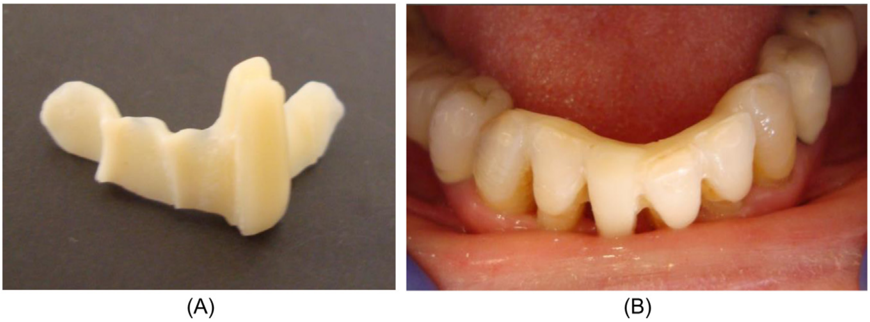

Figure 8.2 (A) An example of indirect FRC splint; (B) fixing the periodontally mobile mandibular anterior teeth with an FRC splint.

Ash, 1981; Serio and Hawley, 1999). Periodontal disease and occlusal trauma are most prevalent in the mandibular anterior region. Although occlusal forces may be lower in this region compared to other regions of the mouth (Hellsing, 1980; Judge et al., 2003), stress levels might be higher due to less bone thickness.

8.1.2 Orthodontic splinting

Splints are also indicated as fixed appliances after alignment of the malpositioned teeth following orthodontic treatment (Fig. 8.3). The influences of the periodontal and gingival tissues, unstable positions of the teeth and continued skeletal growth are considered to be the major causes of relapse after removal of fixed appliances (Melrose and Millett, 1998). Among several types retainers (Lai et al., 2014), usually orthodontists prefer fixed retention, as removable appliances decrease patient compliance. The results of orthodontic treatment are potentially unstable. Hence, permanent or semi-permanent retention with a fixed retainer is essential (Artun et al., 1997; Dahl and Zachrisson, 1991; Stormann and Ehmer, 2002). Typically, fixed retention is preferred in both maxillary and mandibular dental arches except for two clinical situations, namely extraction and maxillary expansion. In such cases, a combination of fixed and removable retainers is preferred in the maxilla (Lai et al., 2014). Malocclusion type (91%), patient compliance (87%), oral hygiene (84%) and patient expectations (81%) play a role when deciding for the retainer type (Sfondrini et al., 2014).

8.1.3 Trauma splinting

In trauma cases due to exposure to impact forces or accidents, splint rigidity should be adapted depending on the type of trauma (Andersson et al., 1985; Berthold et al., 2009; Flores et al., 2007; Oikarinen, 1990). Rigidity can be influenced by the selected reinforcement material (Berthold et al., 2009; Mazzoleni et al., 2010; Oikarinen et al., 1992; Oikarinen, 1988; von Arx et al., 2001), the splint extension (Berthold et al., 2011; Ebeleseder et al., 1995), and the extension of the adhesive points (Schwarze et al., 1995). In addition to the treatment-related requirements,

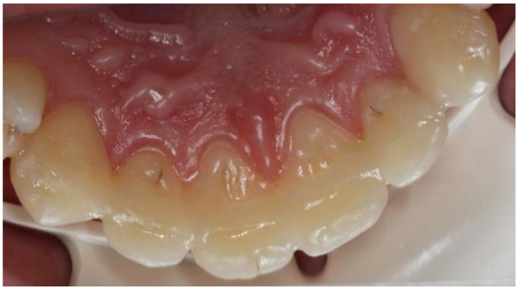

Figure 8.3 An example of direct FRC splint bonded to palatal surfaces of maxillary anterior teeth after completion of orthodontics used as lingual retainer.

some patients pose higher aesthetic demands because of public exposure during the splinting period. One approach to solving this problem could be the attachment of the splint to the palatal site of the teeth (Berthold et al., 2012).

Clinical situations that require tooth stabilization include mainly periodontal splinting of the severe mobile teeth after elimination of the periodontal disease (Serio, 1999; Vogel and Deasy, 1977), orthodontic retention (Dahl and Zachrisson, 1991; Lie Sam Foek et al., 2008; Lumsden et al., 1999), repositioning or re-implantation of the avulsed teeth that were subjected to trauma (Hinckfuss and Messer, 2009), and splinting teeth in primary or secondary occlusal trauma. However, not every mobile tooth should be splinted, and the duration for splinting could be short-term or long-term depending on the situation. Furthermore, for splint applications, biological and biomechanical principles should be considered in a multidisciplinary approach (Serio, 1999; Vogel and Deasy, 1977). The main objectives for splinting teeth in patients with advanced periodontal problems are to achieve periodontal healing, and to create an oral environment in which tooth mobility is at a tolerable level or at least is no longer increasing and the patient is able to function comfortably (Lemmerman, 1976). Often such patients avoid chewing on or incising food with such mobile teeth, yielding to soft diet restrictions.

8.2 Splint Materials and Types

Various materials and techniques have been used to create periodontal splints, such as resin composite in combination with adhesive systems alone (Bernal et al., 2002; Rosenberg, 1980; Serio, 1999), orthodontic wires (Rosenberg, 1980; Stoller and Green, 1981) in combination with resin composites, or preimpregnated fiber-reinforced composite (FRC) in combination with resin composite (Bernal et al., 2002; Serio, 1999; Tokajuk et al., 2006). An important aspect for the selection of a splint type is the mechanical interaction between splinting materials and tooth substrates (Sewón et al., 2000; Torbjorner et al., 1996; Vallittu, 1999). However, the impact of bone loss and splint type on the biomechanical response has not been measured yet. Therefore, determining when to splint and selecting the most appropriate technique remains a difficult decision for the clinicians (Kumbuloglu et al., 2011).

Teeth splinting has been traditionally accomplished with full-coverage cast restorations. Crowns joined together have proved to be effective at stabilizing teeth and restoring esthetics. However, it is a very aggressive treatment with extensive tooth structure removal and possible root canal therapy (Brägger and Hirt, 2010; Cordaro et al., 2005; Kreissl, 2007; Siegel et al., 1999). Moreover, full-coverage restorations typically require subgingival margin placement in patients at high risk of gingival recession and margins exposure (Valderhaug and Birkeland, 1976; Valderhaug, 1980).

There are two basic designs of lingual bonded retainers for orthodontic applications, rigid mandibular canine-to-canine retainers, that are attached to the canines only, and flexible spiral wire retainers that are bonded to each tooth in the bonded segment. While the first one is effective in maintaining inter-canine width but less so in preventing individual tooth rotations, the second design is more effective in preventing rotations of the teeth (Labunet and Badea, 2015).

Clinical failure of bonded retainers usually occurs at the wire composite interface, at the adhesive-enamel interface, or in the form of fracture of the wire. Failure of a retainer may lead to undesired tooth movement. One disadvantage of fixed retainers is that they complicate oral hygiene procedures and favor the accumulation of plaque and calculus. Nevertheless, the presence of a bonded retainer appears to cause no increase in incidence of caries or periodontal disease (Butler and Dowling, 2005) and the use of interdental cleaning aids is required in order to ensure adequate oral hygiene.

8.3 Fiber-Reinforced Composite Splints

Due to the bonding abilities with their resin-impregnated surfaces, FRC materials are commonly for splinting periodontally mobile teeth. FRC materials combine the adhesive properties of resin composite with the reinforcing features of fibers to provide stabilization with no additional need for tooth preparation as retention is accomplished by resin adhesion to etched enamel (Ayna and Celenk, 2005; Freilich et al., 2002; Pollack, 1999; Unlu and Belli, 2006). Although fiber-reinforced composite is a popular alternative to traditional full-coverage splinted restorations for the treatment of periodontally mobile teeth, the technique has some limitations (Brägger and Hirt, 2010; Cordaro et al., 2005; Kreissl, 2007; Siegel et al., 1999). The most common failure types are wear and debonding of the splint. When resin composite wears to the point of exposing the fiber, it weakens the splint and the FRC becomes a source of irritation to the tongue (Ayna and Celenk, 2005; Valderhaug and Birkeland, 1976; Valderhaug, 1980). Another limitation is debonding under repeated tensile stress during function (Strassler, 2009). Finally, the choice of optimal fiber position and size is frequently limited to the opposing teeth contacts (Pollack, 1999; Unlu and Belli, 2006). Most of these limitations occur in the maxillary arch and in closed bites whereas mandibular FRC splints provide generally higher survival rate and better clinical performance (Freilich et al., 2002; Strassler and Serio, 1997). One possibility for overcoming this problem is to position the FRC on the buccal side of the maxillary teeth. Labial splinting could increase longevity of FRC splints as resin composite would be protected from functional wear. Also, adhesion would be improved as the embedded fiber will be on the tensile side and occlusal forces will then be directed in a more favorable direction (Pollack, 1999; Strassler et al., 2001). Finally, no limitation exists for optimal fiber positioning because there is no occlusal contact with the opposing teeth. Certainly, once fiber-reinforced composite is bonded to the buccal surface of the teeth, some form of veneering is required in order to mask the fiber and restore natural aesthetics.

Previous experience with cast metal resin-bonded fixed dental prosthesis (RBFDP) suggests not to use rigid restoration for such purposes (Strassler and Brown, 2001; Strassler et al., 1995; Van Heumen, 2009). The high debonding rate of RBFDPs in periodontal patients has been linked to the rigidity of metal that transfers the entire shear and torsional stress generated by the mobile teeth to the adhesive interface (Iniguez and Strassler, 1998; Karbhari and Strassler, 2007). High elasticity modulus metal structures present the highest level of interfacial adhesive stress whereas flexible composite materials demonstrate the most favorable stress transfer within the tooth/restoration complex (Strassler and Serio, 1997). This single-appointment, minimally invasive technique is a more conservative, less complicated, less expensive alternative to traditional full-coverage restorations for the treatment of severe periodontal patients. However, although long-term follow-up studies of full-coverage splinted restorations have been published, there are no comparable data for the presented adhesive technique, and its efficacy is still to be validated as a function of time (Kumbuloglu, 2011; Novelli, 2015). Furthermore, splinting with FRCs is solely a stabilization technique and does not provide much aesthetic improvement for the patient (Pollack, 1999; Strassler and Brown, 2001; Strassler and Serio, 1997; Strassler et al., 2001).

In orthodontics FRCs are used for active and passive applications such as increasing anchorage units and post-orthodontic tooth retention (Freilich et al., 1998). Fibers provide high mechanical properties, while resin composite offers good aesthetic benefits (Bearn et al., 1997; Vallittu, 1999). FRCs is also biocompatible (Liu, 2010) and since they are metal-free, they could be indicated for patients who are allergic to metals or in subjects screened by Nuclear Magnetic Resonance (RMN). Another important aspect of using FRCs as retainers is aesthetics. FRCs are barely visible and do not affect the teeth-translucence (Karaman et al., 2002). Considering the higher number of adult patients who request an orthodontic therapy (Cacciafesta et al., 2008), this aspect is also gaining importance in adult orthodontics.

8.4 Perio-Prosthetic and Ortho-Prosthetic Splint Combinations

The loss of a single anterior tooth may be a catastrophic event for a patient (Ambic et al., 2013). In advanced periodontal disease such a loss is unfortunately often accompanied by adjacent tooth mobility due to severe bone loss. Furthermore, periodontal disease also chronically dislodges teeth due to the masticatory movement of the mobile teeth, which seriously affects anterior aesthetics, especially for the maxillary anterior teeth. Therefore, prosthodontic rehabilitation is often necessary to restore aesthetics and function in periodontally compromised dentition (Dhingra, 2012; Kourkouta et al., 2007).

Prosthodontic treatment for periodontally-involved anterior teeth usually includes dental implants, full-coverage FDPs, RBFDPs, or partial removable dental prostheses (PRDPs) (Dhingra, 2012; Kourkouta et al., 2007; Minami et al., 2012). Implant restoration is the first choice for the treatment of suitable systemic and local conditions. However, the patient and site-risk profile should be assessed in combination with a cost−benefit analysis based on the patient's expectations for the implant treatment of periodontitis. This analysis should be followed by an extended observation period after the completion of periodontal therapy (Donos et al., 2012). Therefore, the majority of patients do not immediately choose implant prostheses. Partial or full coverage FDPs are alternative treatment options that exhibit high mechanical strength and resistance to dislodgement but require tooth preparation (References should be in chronological order.). They may also increase the torque of the abutment teeth, resulting in mobility. Therefore, many patients decline RBPRDPs in favor of a conservative alternative that requires less tooth reduction, less gingival disturbance, and reduced chair time (Aggstaller et al., 2008; Kreulen and Creugers, 2013; Minami et al., 2012). The fiber-reinforced, composite-resin (FRC) bonded splint-bridge is a type of RBPRDP that involves FRC splinting adjacent to the mobile tooth. This approach can provide a simple, comfortable, affordable, non-invasive and aesthetic rehabilitation program for periodontally-involved anterior tooth loss (Chafaie et al., 2013; Khetarpal et al., 2013). Extracted teeth or composite resins could be used as pontics (Purra and Mushtaq, 2013; Singh et al., 2014). Usually, the FRC-bonded splint-bridge can be used as a long-term or temporary restoration for periodontal disease before or during implantation (Kermanshah and Motevasselian, 2010; Meiers and Freilich, 2006). However, few long-term clinical studies have examined outcomes for FRC-bonded splint-bridges in periodontally-involved anterior maxillary and mandibular teeth (Kumbuloglu et al., 2008, 2011; Sewón et al., 2000; Strassler and Serio, 2007).

The prosthodontic treatment of periodontally-involved anterior teeth with mobility and chronic dislodgement is often a dilemma when the extraction of dislodged teeth seriously affects anterior aesthetics. This challenge is especially common for severe labial or lingual dislodgement as the effect of rehabilitation is uncertain, irrespective of the extraction of dislodged teeth. Recently, adequate orthodontic and periodontal treatment has been sought to improve the periodontal condition and anterior aesthetics (Cao et al., 2015; Cirelli et al., 2006; Tavares et al., 2013). However in such cases, periodontal breakdown causes pathologic migration of teeth, making the orthodontic treatment more complicated (Agarwal et al., 2014; Czochrowska and Rosa, 2015; Kokich, 1996). At present, few clinical studies have examined the aesthetic restoration of periodontally-involved anterior teeth with mobility and chronic dislodgement. The development of silanized and resin-impregnated FRC materials has provided potential new approaches for stabilizing hypermobile teeth or replacing teeth in a conservative manner (Kumbuloglu et al., 2011; Meiers et al., 1998).

Splints in dentistry are classified as provisional or permanent and they may be either fixed or removable (Nymann and Lang, 1994). They may be constructed of various materials being as simple as a bonded composite resin button connecting one tooth to the other allowing better cleanability of the teeth. Yet, this type of stabilization is considered transient in nature, due to the inability of composite resin to accommodate shear forces (Nathanson, 1981). Several clinical studies in the field of orthodontics reported high debonding rates when the mandibular or maxillary teeth are splinted with the use of metal wires (Dahl and Zachrisson, 1991; Lie Sam Foek et al., 2008; Lumsden et al., 1999). Although the reasons for these failures are not well studied, several factors are described in the dental literature such as insufficient composite material and/or abrasion of the composite, less abrasion resistance and wear as a consequence of chewing or tooth-brushing (Bearn, 1995; Bearn et al., 1997), thickness of the wire (Foek et al., 2009), and intermittent forces of mastication (Bearn, 1995; Bearn et al., 1997). Another reason for debonding rates was attributed to the forces resulting from tension in the wire or between the wire and the teeth when the wire has not been adapted properly to the surface of the teeth (Bearn, 1995). Nevertheless, detachment of the bonded wire retainers may have negative consequences for the treatment result, possibly making re-treatment necessary (Foek et al., 2009). In fact, teeth without mobility are splinted in orthodontics after the end of the orthodontic treatment to avoid relapse response of the teeth to their original positions, whereas in peridontally compromised patients, usually splinting is achieved on mobile teeth at various grades. In that respect, theoretically, resin-impregnated FRC materials are well suited for stabilizing hypermobile teeth that interfere with chewing function because of their elastic modulus, aesthetics, pliability, and the possibility of chemical adhesion both to the composite materials and the tooth, as opposed to the metal wires (Strassler et al., 1999). Resin pre-impregnated FRCs has suitable flexural modulus and flexural strength to function successfully in the mouth as restorative materials (Freilich et al., 1999; Meiers et al., 1998). It is considered that elimination of the metal wire in the retainer by using FRC systems would lead to more stable bonding since adhesion of such retainers would solely rely on adhesion of the flowable composite or the resin matrix of the FRC to the etched and bonded enamel. Preimpregnated FRC systems usually involve monomers such as urethane dimethacrylate (UDMA), urethane tetramethacrylate (UTMA), bisphenol glycidylmethacrylate (Bis-GMA) or polymethylmethacrylate (PMMA) (Freilich et al., 1999). Evidence is still lacking for whether ultra high molecular weight polyethylene (UHMWPE) fibers could be used to fabricate durable FRC restorations (Gutteridge, 1992). Criticism has been focused on the inadequate interfacial adhesion between polyethylene fibers and dental polymers, compared to glass fibers that can be silanized (Vallittu, 1998). Development of silanized and resin-impregnated, FRC materials has provided the potential new approaches for stabilizing hypermobile teeth or replacing teeth in a conservative manner (Meiers et al., 1998). Unfortunately, no long-term clinical study is available to date with such FRCs used for splinting purposes (Sewón et al., 2000; Tokajuk et al., 2006).

Since the construction should not exceed 2 mm, the FRC could even weaken the fiber/composite complex. The required thickness of the fiber−composite complex could be reached when box or groove preparations are made in the lingual surfaces. However, this would then not fit in the minimal invasive treatment approach. For this reason, usually no mechanical retentions or preparation were made on the enamel surfaces. In clinical practice, the complete thickness of the whole complex in a splint could still be considered high. The dilemma however remains how to control the thickness of the bonded retainers clinically (Kumbuloglu et al., 2011).

Because E-glass FRC has great aesthetic and economic superiorities, are easy to repair and require no preparation on sound teeth, they present an alternative treatment choice over other invasive restorative procedures. However, it should not be forgotten that fabrication of FRC requires a meticulous work. Splinting affords no guarantee that occlusal stress can be completely eliminated. Although extraction is an appropriate treatment for extremely mobile teeth, it may not resolve all the underlying pathology if the aetiology of the mobility is not established in the first place. Considering the clinical failures with stainless steel retainers related to debonding (Dahl and Zachrisson, 1991; Lie Sam Foek et al., 2008; Lumsden et al., 1999), the adhesion aspect especially warrants the comparison of FRC materials to their metallic counterparts clinically. When the metal wire is bended and placed on the lingual surfaces of the teeth to be splinted, the initial contact with the etched enamel is the wire itself. This may then act as debonding sites for crack initiation. This kind of phenomena is not valid for the FRC splint since mainly the flowable composite is in contact with the bonding agent treated enamel, providing more reliable adhesion. Nonetheless, randomized controlled clinical trials would be conducted to compare whether FRCs have advantages over metal wires. It should however be noted that metal wires usually require impression making and bending the wires on the plastic model, whereas FRC splints do not require such clinical steps as they can be bonded directly in one session (Kumbuloglu et al., 2011).

In congenitally missing lateral teeth cases, it is not always possible to place implants after the orthodontic rehabilitation. The most prominent issue in these cases is insufficient bone support. In these cases, ortho-prosthetic combination of FRC restorations are applicable for both compensating uni- or bilateral teeth loss and provide retaining of orthodontic rehabilitation.

8.5 Clinical Cases With FRC Splints

Periodontal splints can be applied by using either direct or indirect technique. Direct technique is usually preferred in clinical practice when there is no loss of teeth and splinting would be done only due to periodontal disease. When the combined method is to be used especially in those cases where there is tooth loss, that is, both splint and adhesive RBFDP will be made, the indirect technique may be applied. In both cases, positioning the fiber in the tensile region of the reconstruction is crucial (Fig. 8.4).

Figure 8.4 Positioning the FRC on the lingual surface of the teeth.

8.5.1 Direct technique

The teeth on the labial and lingual surfaces were cleaned with pumice using a prophylaxy brush on a slow-speed hand-piece at 3000 rpm. All splints were made under rubber-dam. In order to avoid excess of adhesive resin or resin composite, orthodontic elastic bands were placed at the interdental spaces between the teeth to be splinted after placing the rubber-dam. With small amounts of resin composite, all mobile teeth were temporarily attached to each other at their labial surfaces and photo-polymerized for 10 seconds. The purpose of this step was to stabilize the mobile teeth and to avoid any displacement during splinting. For this process, the enamel surfaces were not etched and no surface preparations were made. Enamel surfaces on the palatal side were then etched with 37% orthophosphoric acid for 60 seconds. After rinsing with water and air-drying, the corresponding intermediate adhesive resin was applied onto the surfaces using a microbrush, and gently air-dried and photo-polymerized for 20 seconds. A thin layer of flowable composite resin was applied on the enamel surfaces and left unpolymerized. Then, a previously measured length of FRC material was placed in the bed of the flowable resin with the aid of a silicone mold available in the FRC kit. The silicone mold with the FRC material in its groove in the middle was exerted onto the lingual surface of the tooth on the flowable resin with gentle pressure. In the cases where the tooth was lingually positioned in relation to the neighboring teeth, the silicone mold was pressed not only on the lingual but also at the approximal sites to achieve continuous alignment of the FRC. FRC together with the flowable composite was photo-polymerized for 40 seconds per tooth surface. Whilst polymerization on each tooth, the rest of the silicone mold was protected from the polymerization device with a metal hand instrument. When the whole FRC was polymerized, the silicone mold was removed and the exposed surfaces of the FRC were covered by the same flowable composite and photo-polymerized again for 40 seconds. All FRC splints were made with one bundle of FRC material, their surfaces were completely covered with resin composite and each layer was again photo-polymerized for 40 seconds from all aspects. Finally, after occlusal adjustments, all FRC splints were finished using fine diamond burs to remove the excess resin composite. Subsequently, the composite surfaces were polished with coarse, medium, fine, and ultrafine finishing disks in sequence using a hand-piece at 3000 rpm in order not to expose fibers.

8.5.2 Indirect technique

All teeth were temporarily splinted from the labial surfaces by using small pieces of resin composite without any tooth surface preparation in order to avoid any displacement of the mobile teeth during impression making. Maxillary-mandibular impressions and bite registration were made with a silicone-based impression material, and working casts were prepared in the laboratory. A combined restoration with pontics to replace the missing tooth and a splint was fabricated with a laboratory resin composite together with the FRC material.

Restoration was intraorally tried-in and bonded with a luting cement. The bonding surfaces of the retainer parts of FRC FDPs were roughened using a green stone finishing bur with a low-speed handpiece, or grooves are opened to prepare room for the FRC followed by application of the bonding agent and storage in the dark for 5 minutes. Meanwhile, the abutment teeth were cleaned with pumice using a prophylaxis brush on a low-speed handpiece. Enamel surfaces on the palatal side were then etched with 37% orthophosphoric acid for 60 seconds. After rinsing with water and air-drying, the corresponding intermediate adhesive resin was applied onto the surfaces using a microbrush, gently air-dried. The splint could be cemented with dual, light, or chemical curing composite resin luting cement according to manufacturer's directions, and photo-polymerized for 40 seconds from all aspects. Finally, after occlusal adjustments, FRC splint was finished using fine diamond burs to remove the excess resin composite. Subsequently, the composite surfaces were polished with coarse, medium, fine, and ultrafine finishing disks in sequence using with a hand-piece at 3000 rpm in order not to expose the fibers (Fig. 8.5A–D).

8.5.3 Clinical follow up protocols

Oral hygiene protocols for the use of interdental brushes and flosses should be practiced after treatment once more and the patients should be recalled for periodical follow-up controls first at 6 months and thereafter annually. Periodontal health, tooth mobility, level of oral hygiene, and the condition of FRC splint in all patients should be assessed during the follow-up controls. Patient satisfaction surveys should be interviewed regarding their satisfaction with their restorations (regarding general satisfaction) using a visual analogue scale (VAS). The evaluation protocol should also involve technical failures (chipping, debonding, or fracture (tooth/restoration)) and biological failures (caries). On the periodontal aspect, periodontal pocket depth (PPD) and clinical attachment level (CAL) should be measured 6 months after splinting and thereafter annually.

Figure 8.5 (A) Preparation of grooves on the lingual surfaces of the anterior teeth in enamel to create room for the FRC splint; (B) measurement of the fiber length using orthodontic elastics; (C) placement of the fiber onto the grooves; (D) covering the FRC with resin composite and photo-polymerization.

8.5.4 Clinical survival of splints

Today, repair actions using surface conditioning methods and resin composites prolong the survival of resin-based restorations (Hickel et al., 2007). Therefore, restorations that remain functional for many years after repair procedures cannot be considered as catastrophic failures. Dental literature contains information on FRC splint construction in case reports but longitudinal studies are limited or they report only short-term results (Sewón et al., 2000; Tokajuk et al., 2006). One such study presented 1-year follow-up of functional rehabilitation of a patient with severely advanced, rapidly progressing marginal bone loss treated FRC material. However, periodontal findings were only descriptive (Sewón et al., 2000). In another clinical study, periodontal outcome of stabilized mobile teeth with an E-glass fiber (Fiber-Kor) was assessed. In that study, 56 patients were enrolled. The study presented the results only after 10 months where PPD decreased by an average of 0.58 mm after teeth stabilization. PPD decrease in another study between 6-month and 18-month observations was an average of 1.2 mm (Kumbuloglu et al., 2011). Additional information is needed on whether this is due to the limited number of patients or the difference in FRC materials used.

When the clinical survival rate of fixed orthodontic retainers is considered current, in vivo studies on survival rate take little notice of the role of the material used for bonding of the fixed retainer (Labunet and Badea, 2015). It is not possible to draw a conclusion on the reliability of new types of retainers, glass fiber reinforced resin composite resin, or polyethylene FRCs compared to multistrand stainless steel wire, as there are no studies that obtained statistically significant differences between different types of splint materials, and the heterogeneity of the studies is very high. The multistrand wire remains to be the gold standard for fixed retention in orthodontics. Although it is a logical outcome that retainer survival is dependent on the application technique, there seems to be no research outcome proving that operator experience and moisture control are essential, nor that patient's age, gender or location have statistically significant effects on survival rates.

8.6 Concluding Remarks and Future Trends

As a result of periodontal disease or trauma, tooth mobility could be avoided through splinting that restores function and also eliminates tooth extraction. Combining an FRC-bonded splint, FDP, fiber post and/or resin veneer for minimally invasive prosthodontic treatment in the aesthetic zone is a good choice for periodontal patients. The use of FRC splints for periodontal, orthodontic or trauma splinting have different functions but the common failure types are debonding and fractures. Whether the thickness of the resin composite impairs the survival of the splints or the tooth mobility needs to be investigated, and failed splints should be evaluated from this aspect in the future.

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Fillings and core build-ups

9

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Chapter Outline

9.1 Introduction

Conservatively, the treatment of lost tooth structure involves direct composite restorations, i.e., particulate filler composite (PFC) restorations. Beside the ability to bond to hard tooth tissues, mediated by adhesive systems, they feature the advantage of natural shade and are less expensive compared with cast gold and ceramic indirect restorations (Manhart et al., 2000). The use of resin composites increased tremendously during the last two decades. Today, resin composites are selected on a regular basis for direct and laboratory-made posterior restorations, as an extension to their original indication, which was limited to direct restorations in anterior teeth. Their use has been widened not only to the posterior intra-coronal area, but also to extra-coronal restorations (Fennis et al., 2014). In addition, resin composites came into focus for the fabrication of resin-bonded fixed dental prostheses (RBFDP) after the introduction of fiber-reinforced composites (FRC). However, insufficient material properties limited the success of composite restorations in high stress-bearing areas (Manhart et al., 2004; Wilder et al., 1999). Dental composite resins were introduced to the dental community in 1960s (Bowen, 1963). Since then, after many significant material improvements, composite resin still suffers a lack of mechanical properties and problems related to polymerization shrinkage. Resin composite restorations have shown good overall clinical performance in small and medium sized posterior restorations with annual failure rates between 1−3%

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(Demarco et al., 2012; Manhart et al., 2004). Secondary decay and fracture are among the most important reasons for clinical failure (Brunthaler et al., 2003; Demarco et al., 2012). Survival of posterior restorations strongly correlates with the size of the restorations. Bernardo et al. reported an increase in annual failure rate from 0.95% for single surface restorations towards 9.43% for four or more surface restorations (Bernardo et al., 2007). Large restorations showed to be more prone to fracture-related failures resulting in decreased longevity (Opdam et al., 2007a; Van Nieuwenhuysen et al., 2003). Higher susceptibility of large resin composite restorations to fracture can be related to the use of glass-ionomer lining material, strength-related properties of the composite material itself, and patient factors like bruxism (Demarco et al., 2012; Opdam et al., 2007b). Besides restoration size also the endodontic status of a tooth strongly affects the longevity of composite restorations. Clinical studies revealed a decreased longevity for composite restorations in endodontically treated teeth, with an increased annual failure rate of 2−12.4% in comparison to vital teeth (Demarco et al., 2012). Furthermore, nonvital teeth are susceptible to unfavorable subgingival cusp fractures (Fennis et al., 2002). The above-mentioned reasons make the restoration of endodontically treated teeth a true challenge.

It is clear from the literature that contemporary resin composites still demonstrate limitations due to their insufficient mechanical properties when used in large restorations. Due to failures of this kind, it is still controversial as to whether restorative composites should be used in large high stress-bearing applications such as in core build-ups or direct posterior restorations (Manhart et al., 2004; Roulet, 1997). The relatively high brittleness and low fracture toughness of current PFC composites still hinder their use in these large stress-bearing restorations (Wilder et al., 1996; Xu, 1999). Appropriate physical and mechanical properties and satisfactory esthetic are all characteristics that restorative composite resin should fulfill.

Contemporary restorative dentistry uses direct, semi-direct as well as indirect restorations to restore lost tooth tissue, with biomimetics as the new driving force. Biomimetic dentistry tries to mimic nature by studying the structure, function, and biology of the tooth organ as a model for the design and engineering of new or improved materials and techniques to restore or replace teeth in a biomechanically optimal way (Magne, 2012). From a biomimetic point of view, we strive to replace lost tooth tissue by biomaterials with similar physical properties, especially with reference to elastic modulus, strength, and thermal expansion coefficient (Magne and Belser, 2002). A well accepted biomimetic restorative approach advocates replacing enamel with feldspathic porcelain or glass ceramic, and dentine by hybrid composites (Magne and Belser, 2002; Magne, 2006). Although such an approach seems effective, there are still relevant mechanical properties, such as fracture toughness, that are not taken into account. Fracture toughness of hybrid PFC is still lower than that of dentine (Manhart et al., 2000). Furthermore, the microstructure of hybrid composite does not resemble that of dentine. Hybrid PFC consists of filler particles embedded in a resin matrix, while dentine consists of collagen fibers embedded in a hydroxyapatite matrix. Therefore dentine should be rather seen as an FRC. Collagen fibers act as crack stopper and give dentine unique properties by making it resilient, flexible, and tough at the same time. For that reason improvement could be found when taking advantage of a more dentine-like and high toughness composite as dentine replacement.

Research has been conducted to improve the reinforcing phase of restorative PFC in order to increase their safety for use in high stress-bearing areas (Garoushi et al., 2007a). Attempts have been made to change type of filler or filler size and their silanisation (Ferracane et al., 1998). Reinforcing the resin with glass fibers (Garoushi et al., 2007a, 2008, 2013), with FRC-substructure (Garoushi et al., 2006a,b, 2007; Keulemans et al., 2009a, 2010), whiskers (Xu et al., 2003), particulate ceramic fillers (dense and porous) (Zandinejad et al., 2006), and optimization of filler content (Ferracane et al., 1998) are among the methods that have been studied. Some other aspect relating to indirect laboratory-made composites have been investigated by using post-curing to enhance composite strength and toughness (Loza-Herrero et al., 1998; Peutzfeldt and Asmussen, 2000).

Till now, resin composite reinforced with short randomly oriented glass fibers (SFRC) are the most interesting materials because of their close resemblance to dentine at the level of microstructure and mechanical properties. Earlier formulations of SFRC (Alert, Jeneric/Pentron; Nulite F, NSI dental) were already commercialized in the late 1990s as packable composites. Although they exhibited promising mechanical properties (Manhart et al., 2000), clinical problems were encountered concerning surface roughness and wear resistance (Fagundes et al., 2009). In addition, a medium-term clinical study by van Dijken et al. (van Dijken and Sunnegardh-Gronberg, 2006) revealed a high failure rate for one of these SFRCs (Nulite F) due to secondary decay and bulk fracture.

Bulk fracture of these earlier SFRC formulations was related to sub-optimal reinforcement of the polymer matrix by short fibers. In this respect, one should be aware that fiber fillers should have a minimal length, the so-called critical fiber length, in order to optimally reinforce the polymer matrix, meaning that the critical fiber length of the reinforcing fibers are of paramount importance regarding overall mechanical properties of SFRC (Petersen, 2005). Earlier SFRC formulations did not fulfill this requirement. Critical fiber length has also implications towards fracture toughness (K_{Ic}), a property of major influence on the clinical performance of a material. Fracture toughness of earlier SFRC formulations is lower than that of dentine, 2.3 MPa.m$^{0.5}$ and 3.1 MPa.m$^{0.5}$ respectively (Manhart et al., 2000).

Following this knowledge, a new type of short fiber-reinforced composite was launched onto the Finnish market back in 2011 as Xenius Base (stickTech Ltd, Turku, Finland) and re-launched globally in 2013 as everX Posterior (GC Corporation, Tokyo, Japan). It consists of a combination of a resin matrix, randomly orientated millimetre-scale E-glass fibers (0.3−1.9 mm) and inorganic particulate fillers (Bijelic-Donova et al., 2016b; Garoushi et al., 2013; Lassila et al., 2016). The resin matrix comprises cross-linked monomers bis-GMA and TEGDMA accompanied with linear PMMA. This combination of resins enables the formation of the semi interpenetrating polymer network (semi-IPN) during the polymerization of the material, which provides good bonding properties and improved toughness of the resin composite (Lastumaki et al., 2003). The short, random fibers, on the other hand, provide an isotropic reinforcing effect when placed in bulk, which means that the strength of the material is independent of the fracture load direction, i.e., it is same in all directions. Nevertheless, the in origin isotropic SFRC material (3D fiber orientation and fiber reinforcing factor of 0.2) becomes anisotropic when applied in incremental layers up to 2 mm thick, due to alignment of fibers in the plane of application (2D fiber orientation and fiber reinforcement factor of 0.38) (Vallittu, 2014).

This composite was previously reported to exhibit improved mechanical properties regarding strength, fracture toughness, fatigue resistance, and polymerization shrinkage, and to show a more favorable (repairable) type of failure behavior in comparison to PFC (Garoushi et al., 2007a, 2008, 2011; Petersen, 2005). The use of millimetre-scale fiber fillers with a length in range of the critical fiber length, calculated between 0.85 and 1.09 mm (Bijelic-Donova J et al., 2016b), increased K_{Ic} of semi-IPN-based SFRC up to 2.6−3.1 MPa.m$^{0.5}$ (Abouelleil et al., 2015; Bijelic-Donova et al., 2016a; Tsujimoto et al., 2016) in comparison to 1.84 MPa.m$^{0.5}$ for hybrid PFC (Ilie et al., 2012). Hence it can be hypothesized that the replacement of dentine by a high toughness SFRC can reduce bulk fractures and therefore increase longevity of large resin composite restorations.

Interestingly, SFRC has the ability to conduct and scatter the curing light better than conventional hybrid composites and thus it is suitable for use in bulk of 4 mm layer thickness (Garoushi et al., 2015a,b). Wear and surface roughness related limitations of SFRC can be overcome by adopting a biomimetic restorative approach, in which dentine is replaced by SFRC and covered by a more wear-resistant PFC (Fig. 9.1) (Manhart et al., 2000). Such an approach not only has benefits regarding wear resistance but also regarding strength and fatigue resistance. Clinically, it is widely recommended nowadays to use a layer of bulk composite base (dentine-replacing) material in order to improve esthetics, reduce the polymerization stress, and to develop better mechanical properties (Moorthy et al., 2012). The latter is accomplished by decreasing tensile stress concentrations at the restoration interface, and reducing the cuspal strain (Moorthy et al., 2012). Published clinical results of biomimetic or bilayered restorations (Fig. 9.1) containing SFRC as bulk composite

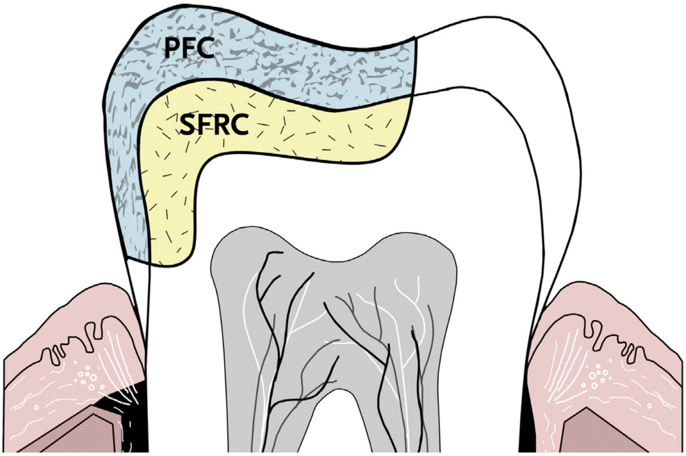

Figure 9.1 Schematic representation of a direct biomimetic restoration: lost dentine is replaced by high toughness SFRC and covered by a wear-resistant enamel-replacing PFC.

base in high stress-bearing areas showed good clinical performance, although the timeframe and cases for this clinical trial were not of such duration and number as to indicate the long-term suitability of the tested restorations (Garoushi et al., 2012).

Bilayered composite structure of SFRC as substructure and PFC as top surface layer (Fig. 9.1) have been evaluated in several in vitro investigations and with different applications (Garoushi et al., 2006a,b, 2007b, 2015a,b; Keulemans et al., 2009b). SFRC had already been used to reinforce large direct composites restorations in vital teeth (Fráter et al., 2014; Garoushi et al., 2012, 2015a,b) as well as in endodontically treated teeth (Ozsevik et al., 2015), as prosthesis infrastructure (Garoushi et al., 2007b,c; Keulemans et al., 2008, 2009a,b), onlay restorations (Garoushi et al., 2006a,b), and endodontic posts (Bijelic et al., 2013, 2011; Garoushi et al., 2007d).

The effect of the thickness of the SFRC substructure versus the thickness of the overlaying PFC, static and fatigue load-bearing capacity of materials combination and the bond strength to the tooth structure are among the issues that have been studied (Garoushi et al., 2006a,b, 2007).

These studies showed that SFRC substructure supports the PFC layer and serves as a crack prevention layer. SFRC substructure's thickness has prior importance, as it influences the failure mode and the crack arresting mechanism. The mechanism of arresting the crack propagation is greatly influenced by the distance between the SFRC substructure and the surface where the stress initiates (Garoushi et al., 2006a,b, 2007). Thus, highly important is how thick SFRC and PFC layers are applied. In vitro was observed that optimal thickness of the veneering PFC composite over the SFRC substructure is between 1 and 1.5 mm (Garoushi et al., 2006a,b, 2007).

Other advantages of SFRC-based biomimetic restorations can be seen at the level of the interface between SFRC and PFC. After application of the SFRC layer some fibers are protruding from the surface (Fig. 9.17), which can be embedded in the veneering PFC layer and form an interface similar to that found at the dentine-enamel junction (DEJ). At the DEJ, collagen fibers originating from dentine extend into enamel creating a fiber-reinforced connection between enamel and dentine. It is known that the microscopic architecture and the unique mechanical properties of the DEJ act as a natural crack arrest barrier (Imbeni et al., 2005).

Theoretically, the significant advantage of this bilayered or biomimetic restoration is its ability to mimic the natural behavior of enamel and dentine. To the author's knowledge, this SFRC is the only available composite resin that structurally mimics the dentine.

In this series of clinical cases an attempt was made, using short fiber composite as bulk base or core material under surface layer of PFC resin, i.e., biomimetic or bilayered composite restorations, to improve the load-bearing capacity and clinical longevity of resin-based composite restorations.

9.2 Case Studies

SFRC (everX Posterior; GC Corporation, Tokyo, Japan) is intended as dentine-replacing material (base filling material) in high stress-bearing areas especially in large cavities of vital and nonvital teeth. SFRC can therefore be used for direct and indirect biomimetic composite restorations, which are indicated for:

1. Restoration of endodontically treated teeth, including core build-ups, post-and-core restorations, and endocrowns
2. Medium to large Class I and II restorations
3. Cusp-protecting and cusp-replacing restorations
4. Crown build-ups
5. FRC-RBFDPs.

9.2.1 Direct biomimetic composite restoration

9.2.1.1 Step-by-step procedure

The following step-by-step procedure describes the restoration of an endodontically treated upper molar with a direct bilayered or biomimetic composite restoration. An existing Class II mesio-occlusal composite restoration and secondary caries is removed (Fig. 9.2). The cavity is designed according to the principles of minimal invasive dentistry and a cusp-protecting preparation is provided at the weakened mesiobuccal cusp (Fig. 9.3). The endodontic access opening is cleaned with a sodium bicarbonate powder spray (PROPHYflex; Kavo) after removal of approximately 2 mm of gutta-percha at the canal orifices (Fig. 9.4). Enamel and dentine are bonded with an adhesive system, preferably a 2-step self-etch adhesive or alternatively a 3-step etch-and-rinse adhesive, after a suitable matrix has been put in place (Fig. 9.5). To obtain an optimal seal of the endodontic access opening, a 1−2 mm layer of flowable bulk fill composite (Surfill SDR; Dentsply) is applied (Figs. 9.6 and 9.7). In vitro research has shown that a bulk fill composite generates less contraction stress during polymerization (Ilie and Hickel, 2011; Rullmann et al., 2012), which improves the bond strength to dentine in cavities with a high

Figure 9.2 Preoperative view: root canal treated upper molar with an existing Class II cavity.

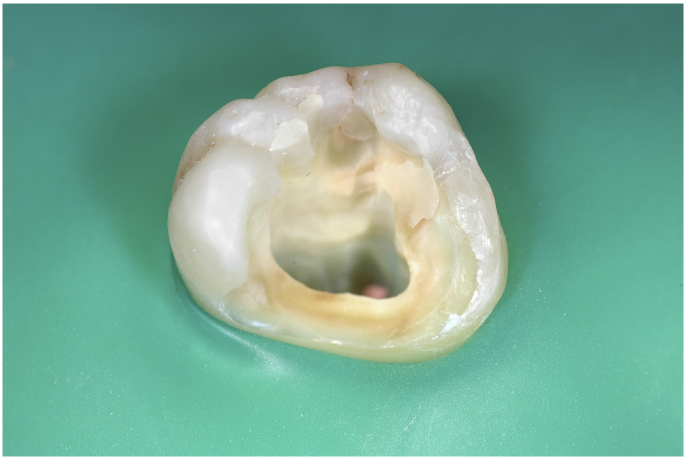

Figure 9.3 Adhesive Class II cavity preparation with reduction of the weakened mesiobucal cusp.

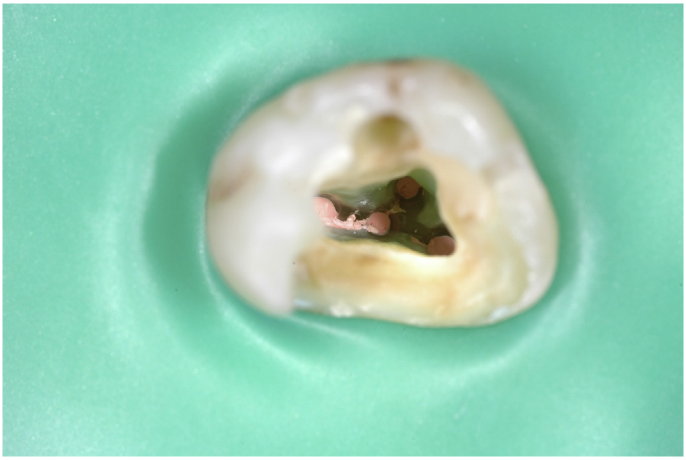

Figure 9.4 Before the cavity and the endodontic access opening was cleaned with prophylaxis spray, 1–2 mm of gutta-percha was removed at the canal orifices with a round carbide bur.

C-factor (Van Ende et al., 2016, 2013). In the first instance the pulp chamber is filled with SFRC (everX Posterior; GC) (Fig. 9.8). To be able to enwrap the SFRC core build-up entirely with enamel-replacing hybrid composite the centripetal filling technique should be adopted. With this technique a multi-surface cavity is converted into a single surface Class I cavity (Fig. 9.9), by building up the walls with a 1-mm-thick layer of hybrid composite (Clearfil AP-X; Kuraray). Another advantage of this technique is the fact that the matrix can be removed, which improves visibility and access to the restoration (Fig. 9.10). The rest of the dentine is replaced with 2 mm

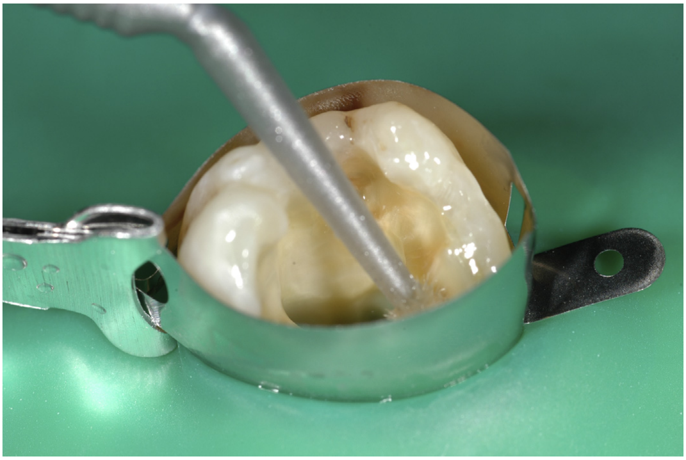

Figure 9.5 Application of the adhesive system.

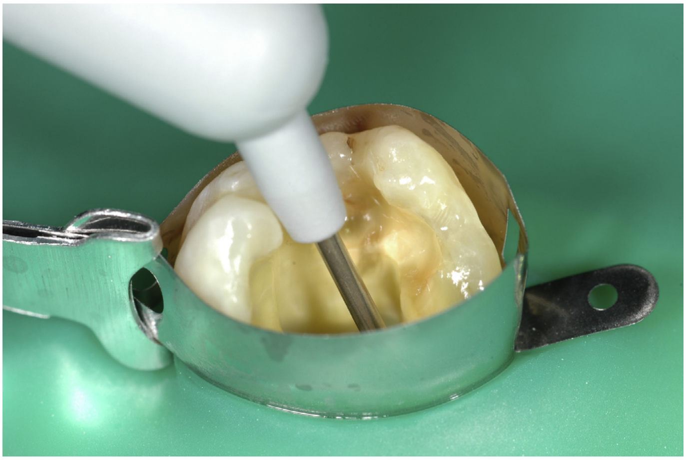

Figure 9.6 Application of a flowable bulk fill composite into the endodontic access cavity.

thick oblique layers of SFRC. To create a natural anatomy the authors prefer to build up each cusp separately (Figs. 9.11 and 9.12). After completion of the dentine build up, there should remain 1−1.5 mm of space for the enamel-replacing hybrid composite in the occlusal area. A final layer of hybrid composite is applied and modeled at the occlusal surface (Fig. 9.13). Following removal of the dental dam, occlusion and articulation is adjusted and the restoration is finished and polished.

9.2.1.2 Clinical case

A 49-year-old male presented with a defective Class II amalgam restoration and a primary carious lesion on a lower second premolar (FDI #45) (Fig. 9.14). The old

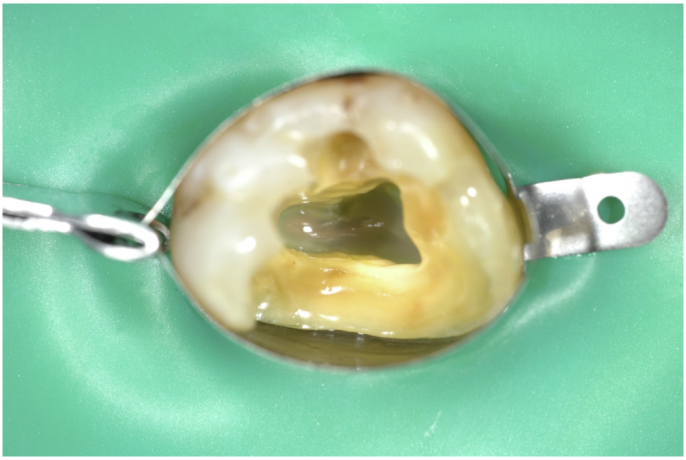

Figure 9.7 Sealed endodontic access cavity. Notice shine-through of gutta-percha due to the high translucency of the bulk fill composite.

Figure 9.8 Pulp chamber filled with a first increment of SFRC.

restoration was removed using a pear-shaped diamond bur (830L; Komet) in a high-speed air turbine. Dental dam was placed after opening the cavity, in order to obtain a dry working field. The minimal invasive cavity was cleaned by sandblasting with 50 μm alumina particles. A three-step etch-and-rinse adhesive (Optibond FL; Kerr) was applied according to the manufacturer's instructions. The resin composite was placed following an incremental filling technique and interproximal contacts were restored by use of metal sectional matrices in combination with separation rings (V3 matrix and ring; Triodent) (Fig. 9.15). The centripetal filling technique was adopted to transform the three-surface cavity into a single surface

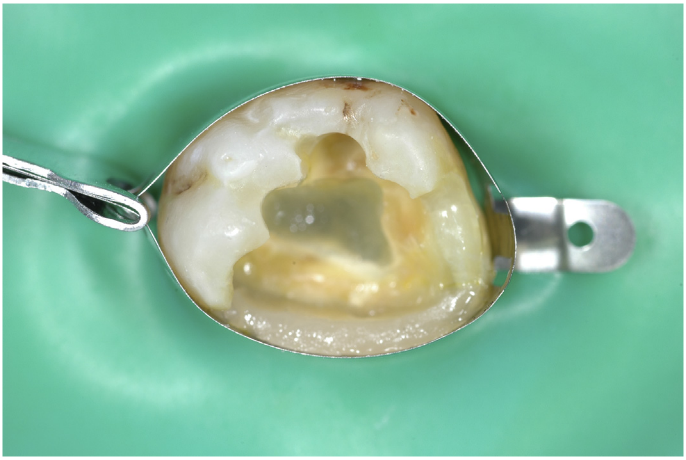

Figure 9.9 Centripetal filling technique: multi-surface cavity converted into a single surface Class I cavity.

Figure 9.10 Matrix can be removed after the walls are rebuilt with hybrid composite.

cavity (Fig. 9.16): a first 1-mm-thick layer of hybrid composite (Filtek Supreme XTE; 3M ESPE) was placed towards the matrix and the subsequent layers (2 mm thick) of SFRC (everX Posterior; GC) were placed oblique (Fig. 9.17). The biomimetic restoration was finalized by placing a final 1.5-mm-thick increment of hybrid composite at the occlusal surface. Each increment of composite resin was light cured with an LED-curing unit (The cure; Spring Health Products) for 40 s. Additional post-curing from the buccal and lingual aspect was performed after matrix removal. Occlusion and articulation was checked and adjusted after removal of the dental dam. The restoration was finished with fine-grit diamond burs (8862

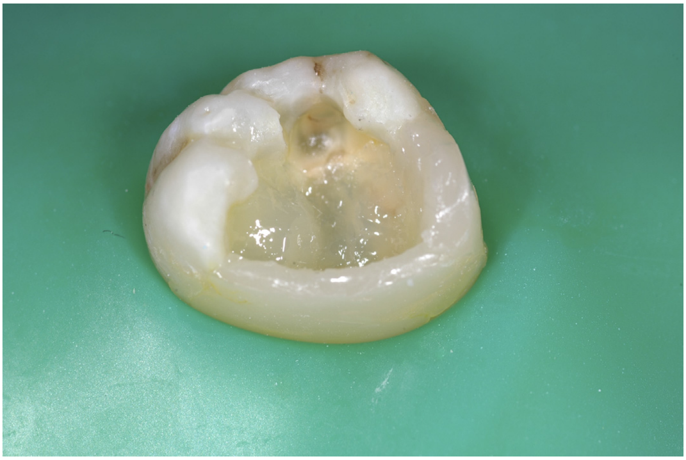

Figure 9.11 Each cusp is built up separately with 2 mm thick increments of SFRC.

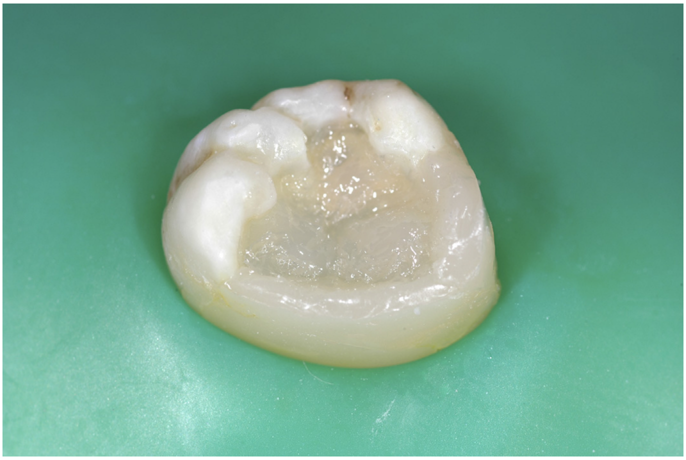

Figure 9.12 SFRC is applied and modeled in anatomical way, leaving 1–1.5 mm of space for a final layer of hybrid PFC.

and 862EF; Komet), abrasive disks (OptiDisc; KerrHawe) and strips (Sof-Lex strips; 3M ESPE) and polished with rubbers (HiLuster; KerrHawe) and brushes (OccluBrush; KerrHawe) (Fig. 9.18).

9.2.2 Indirect biomimetic composite restoration

9.2.2.1 Step-by-step procedure

The second step-by-step procedure describes the restoration of an endodontically treated upper molar, of which the structural integrity is compromised due to

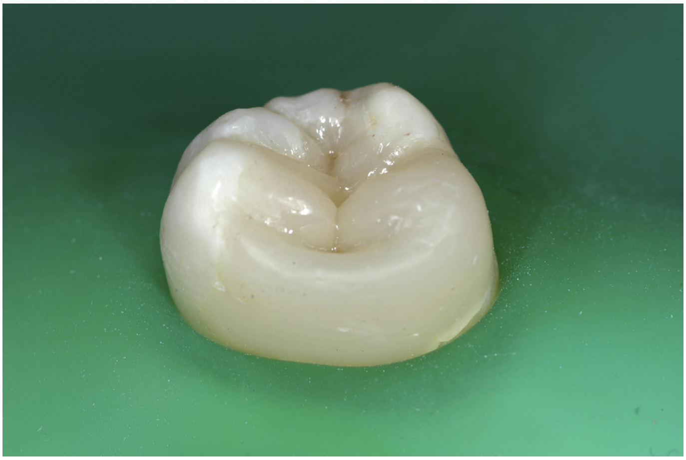

Figure 9.13 Post-operative view: finished direct biomimetic restoration.

Figure 9.14 Preoperative view: clinical view of a defective amalgam restoration in combination with a primary carious lesion at the mesial wall.

extensive loss of tooth tissue (Fig. 9.19), with an indirect bilayered or biomimetic composite restoration. The indirect procedure, as described below, requires two appointments. During the first appointment the tooth receives an overlay preparation. Prior to the preparation of the overlay restoration the endodontic access cavity is sealed with bulk fill composite and the missing dentine is replaced with SFRC in accordance with the procedure described in the step-by-step procedure for direct biomimetic composite restorations (see Section 9.2.1.1) (Fig. 9.20). The rebuilt

Figure 9.15 After removal of the old restoration and elimination of the carious lesion a dental dam is placed and countered sectional metal matrices in combination with a separation ring are installed.

Figure 9.16 Interproximal walls were built up by PFC according to a centripetal filling technique.

tooth receives an overlay preparation designed to provide appropriate thickness for the restorative material and a passive path of insertion with rounded internal angles and well-defined margins (Fig. 9.21). The amount of occlusal reduction depends on the selected overlay material: it is recommended to have at least 1–1.5 mm for resin composite and 2 mm for ceramic (Rocca and Krejci, 2007). For this particular

Figure 9.17 Missing dentine replaced by a semi-IPN-based bulk short fiber composite base (notice protruding fibers from the SFRC surface).

Figure 9.18 Post-operative view: the occlusal part is built up with hybrid composite and the restoration is finished and adjusted in occlusion.

case a resin composite overlay is selected. According the guidelines of contemporary indirect adhesive treatment, an immediate dentine sealing (IDS) concept is adopted (Magne, 2005). This concept advocates adhesive sealing of the entire dentine surface immediately after preparation and prior to impression taking (Magne, 2005). One of the major benefits of this technique is prevention of bacterial

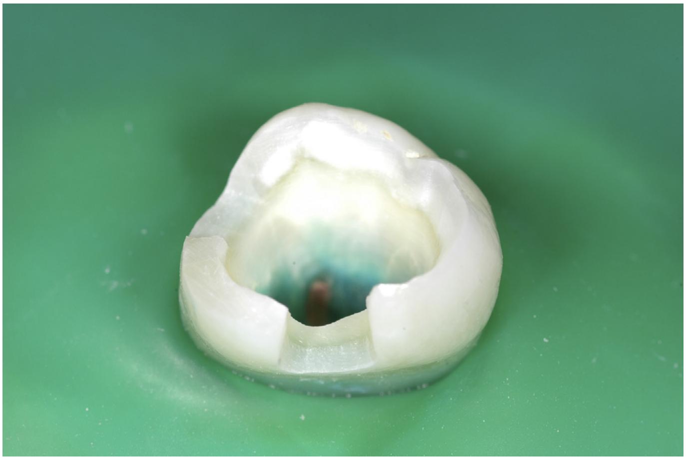

Figure 9.19 Preoperative view: root canal treated upper molar with a three-surface Class II cavity, lost mesio-palatal cusp and weakened remaining walls.

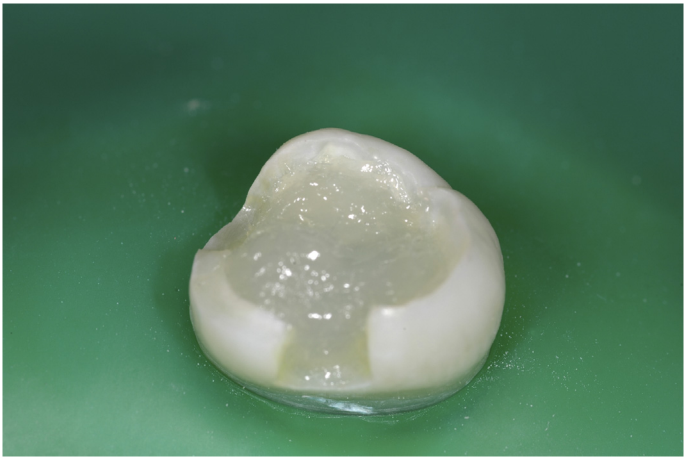

Figure 9.20 Missing dentine replaced by SFRC.

contamination and post-operative sensitivity during provisionalization (Magne, 2005). Furthermore, in vitro research has shown that IDS improves the bond strength to dentine of indirect restorations (Magne et al., 2005). After overlay preparation all freshly exposed dentine needs to be sealed by IDS (Fig. 9.22). Following light curing of the IDS layer, additional light curing is performed after the IDS layer is covered with an air block (Fig. 9.23). In this way the oxygen inhibition layer is polymerized, which prevents interaction with the impression material and the provisional resin composite. The enamel margins are re-finished with a diamond bur to remove excess adhesive resin (Fig. 9.24). Subsequently polyether

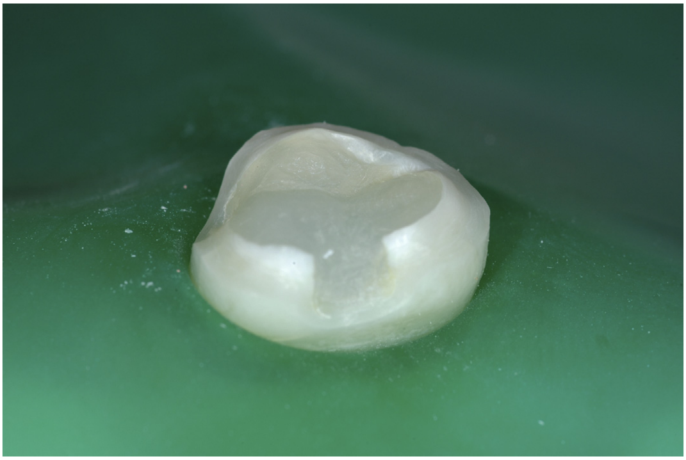

Figure 9.21 Overlay preparation.

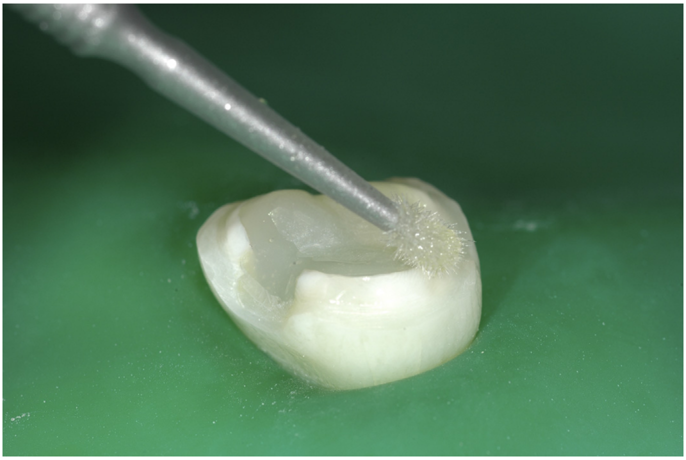

Figure 9.22 Immediate dentine sealing: application of self-etch adhesive system.

impressions (Impregum Penta; 3M ESPE) are taken and a provisional bis-acryl resin composite restoration (Protemp 4 Garant; 3M ESPE) is fabricated and luted with a temporary resin composite luting material (Tempbond Clear; Kerr).

At the beginning of the second appointment the quality (marginal adaptation and proximal contacts) of the resin composite overlay is verified on the working die (Fig. 9.25). After removal of the provisional restoration and clean up of the temporary luting material the fit of the overlay restoration is evaluated in vivo. The color of the restoration is preferably evaluated with a droplet of water or glycerin gel in between the restoration and the tooth tissue. After an initial check of the restoration a dental dam is installed. Next, the restoration needs to be pretreated in an adequate

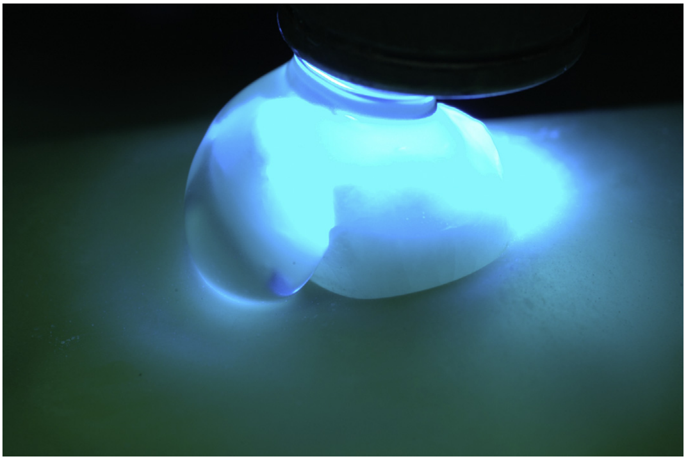

Figure 9.23 Removal of the oxygen inhibition layer: additional light curing after application of glycerin gel.

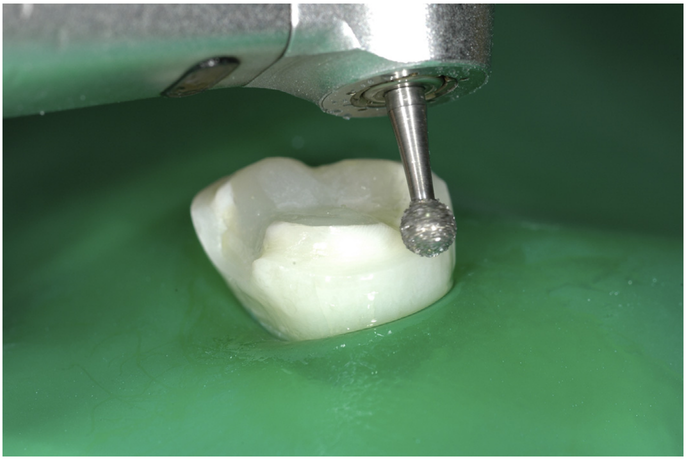

Figure 9.24 Refinishing of the enamel margins prior to impression taking.

way in order to obtain long-term adhesion. The pretreatment procedure is dependent on the selected restorative material and differs for resin composites and ceramics. In this case the procedure for laboratory-made resin composites is described. In the first instance the adhesive interface of the restoration is roughened by sandblasting with 50 μm alumina particles (RONDOflex; Kavo). Subsequently, the adhesive interface is conditioned with an organic silane (Ceramic primer; Kuraray) for 60 s, whereafter the solvent is evaporated with a mild air blow. Finally, a dual-cure bonding agent (Clearfil SE Bond + DC activator; Kuraray) is applied and shielded from ambient light with a dark protective cover. In the second instance the adhesive tooth surface is airborne-particle abraded with 50 μm alumina particles (Fig. 9.26). This

Figure 9.25 Finished hand-layered resin composite overlay as received from the dental laboratory.

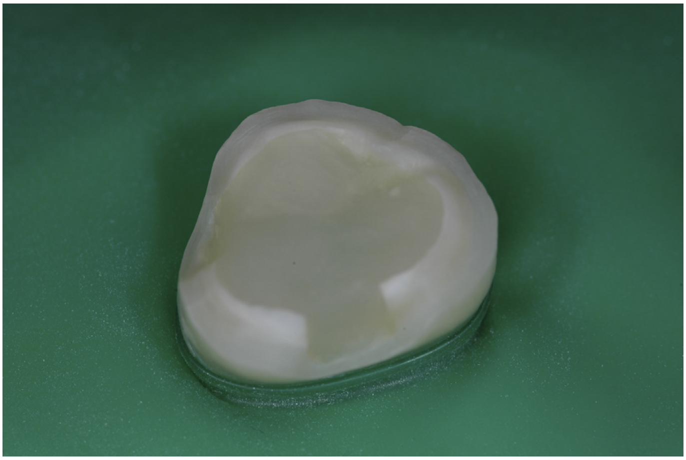

Figure 9.26 Conditioning of the preparation: adhesive surface after airborne-particle abrasion.

procedure cleans and reactivates the IDS layer. Enamel margins were not sealed by IDS, so they are etched for 15 s with phosphoric acid gel (Fig. 9.27). Finally, a dual-cure adhesive system is applied but not cured (Fig. 9.28). The authors prefer a 10-MDP containing mild 2-step self-etch adhesive system (Clearfil SE Bond + DC activator; Kuraray). A flowable core build-up composite (Clearfil DC core automix; Kuraray) is selected as luting agent (Fig. 9.29), because of its improved mechanical properties in comparison to conventional luting composite cements. Alternatively, a flowable PFC or preheated hybrid composite can be used as luting agent in cases were sufficient light-curing through the restoration can be achieved. The overlay

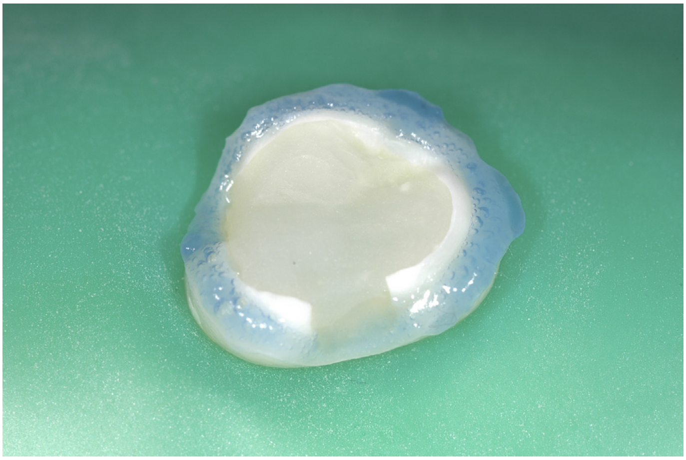

Figure 9.27 Conditioning of the preparation: enamel is acid etched for 15 s with phosphoric acid gel.

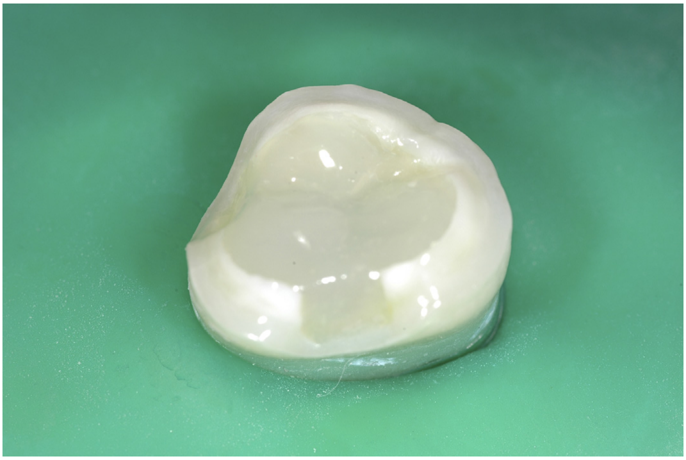

Figure 9.28 Application of adhesive system: dual-cure bonding agent is applied onto the entire preparation without being cured.

restoration is placed onto the preparation under slight finger pressure and seated with the help of a sonic instrument (SONICflex with cem tip; KAVO) (Fig. 9.30). Excess luting composite is removed and the restoration is light cured for 60 s from each surface. To eliminate the oxygen inhibition layer of the luting composite, all margins are covered with glycerin gel and additionally cured for 5–10 s. Occlusion and articulation is checked and adjusted after removal of the dental dam. The restoration is finished with fine-grit diamond burs and strips and polished with rubbers (Fig. 9.31).

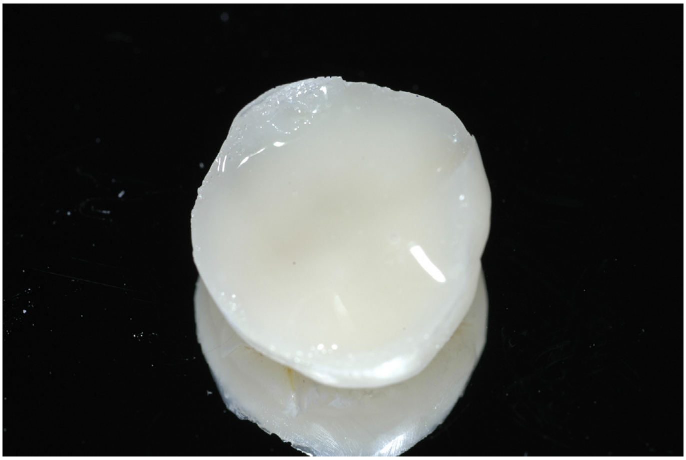

Figure 9.29 Pretreatment of the indirect composite overlay: following sandblasting, conditioning with an organic silane, and application of a dual-cure bonding agent, a flowable core build-up composite is spread onto the adhesive interface of the workpiece.

Figure 9.30 Luting of the overlay: restoration correctly seated onto the preparation. Excess luting composite needs to be removed before light curing.

9.2.2.2 Clinical case

A 53-year-old male patient presented with a palatal cusp fracture of an upper second premolar (FDI #15). Due to extensive loss of tooth tissue it was decided to restore the tooth with an indirect biomimetic composite restoration. During the first appointment missing dentine was built up by SFRC (everX Posterior; GC) and the tooth was provided with an overlay preparation. The dental laboratory produced an overlay restoration made of nanofilled composite blocks (Lava Ultimate; 3M

Figure 9.31 Post-operative view: indirect biomimetic composite restoration after finishing and polishing. Dentine has been replaced on a direct way with SFRC, while an indirect composite overlay serves as enamel-replacing restoration.

Figure 9.32 Finished composite overlay restoration on the working die.

ESPE) through a CAD/CAM workflow (Fig. 9.32). At the beginning of the second appointment the fit of the overlay was checked and a dry working field was obtained with the help of dental dam. The adhesive interface of the abutment tooth was roughened by airborne-particle abrasion with 50 μm alumina particles prior to application of dual-cure adhesive system (Fig. 9.33). The restoration was pretreated by sandblasting with 50 μm alumina particles. After sandblasting the adhesive interface was cleaned with 37% phosphoric acid and subsequently silanised (Fig. 9.34). The adhesive overlay restoration was luted with a dual-cure luting composite (Nexus 3; Kerr) (Fig. 9.35).

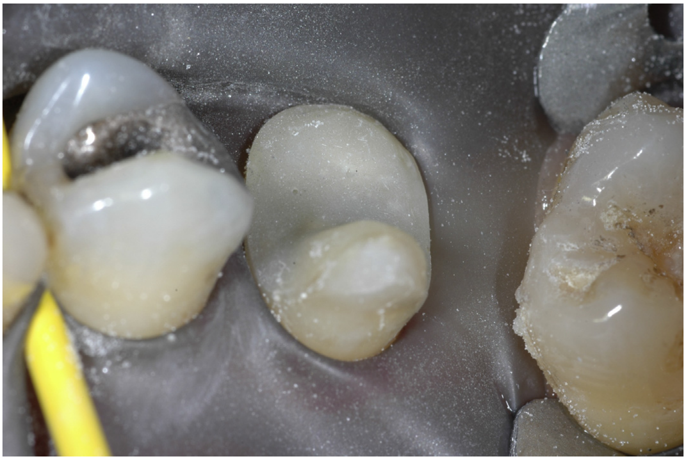

Figure 9.33 Overlay preparation prior to luting: missing dentine was replaced by SFRC.

Figure 9.34 Pretreatment of the indirect composite restoration.

9.2.3 Biomimetic post-and-core restorations

A 57-year-old male patient presented with uncomplicated crown fracture at an endodontically treated upper canine (FDI # 13) due to secondary caries underneath a large composite restoration (Fig. 9.36). The patient requested to repair his tooth in order to postpone the fabrication of a removable partial denture in the upper jaw. Therefore it was decided to restore the tooth by means of a fiber post retained composite crown build-up restoration. After placement of the dental dam, secondary caries was removed. Due to lack of retention it was decided to prepare a post space to accommodate a fiber post, providing retention to the composite crown build-up

Figure 9.35 Postoperative view: occlusal view of the luted restoration after finishing and polishing.

Figure 9.36 Preoperative view: labial view of the fractured root canal treated canine.

restoration (Fig. 9.37). The prefabricated fiber post (DT Light SL; VDW) was luted with a flowable core build-up composite (Clearfil DC core automix; Kuraray) (Fig. 9.38). The missing dentine was replaced with a SFRC core build-up (everX Posterior; GC) (Fig. 9.39) and subsequently veneered with a microhybrid composite (Photo Clearfil Bright; Kuraray) (Fig. 9.40).

9.2.4 *Biomimetic endocrown*

A 44-year-old female presented at the staff clinic of the department of Restorative Dentistry and Endodontology (Ghent University) for endodontic treatment of a

Figure 9.37 Post space preparation after removal of the secondary caries.

Figure 9.38 Luting of fiber post: a prefabricated fiber post was luted with a flowable core build-up composite.

second mandibular molar (FDI #37) (Fig. 9.41). In consent with the patient it was decided to restore the tooth with an endocrown.

The tooth was prepared with a circular butt-joint margin and a central cavity inside the pulp chamber (Fig. 9.42). After isolation of the work field by dental dam and following cleaning of the cavity walls by sandblasting with 50 μm alumina particles (RONDOflex plus 360; Kavo), the endodontic access opening was sealed with a two-step self-etch adhesive (Clearfil SE Bond; Kuraray) and flowable composite (G-aenial Universal Flow; GC) (Fig. 9.42B). Undercuts were filled-up with resin composite (Clearfil Majesty ES-2; Kuraray) in order to guarantee adequate

Figure 9.39 Dentine replacing core build-up with SFRC.

Figure 9.40 Post-operative view: SFRC core build-up was veneered with microhybrid PFC in order to create a direct biomimetic post-and-core restoration.

tissue preservation (Fig. 9.42B). An impression was taken with a medium viscosity polyether material (Impregum Penta; 3M ESPE) and poured in gypsum. A biomimetic restorative approach was adopted for the fabrication of an endocrown (Fig. 9.43). Dentine was replaced by a recently developed semi-IPN-based short randomly oriented FRC (everX Posterior; GC) (Fig. 9.44A and B). SFRC was veneered with a final layer of at least 1 mm PFC (Clearfil Majesty ES-2; Kuraray) serving as enamel replacement (Fig. 9.44C–E). The final restoration was post polymerized in a light oven.

The luting procedure was carried out during a second appointment on the same day. The adhesive surface of the restorations was pretreated in the following

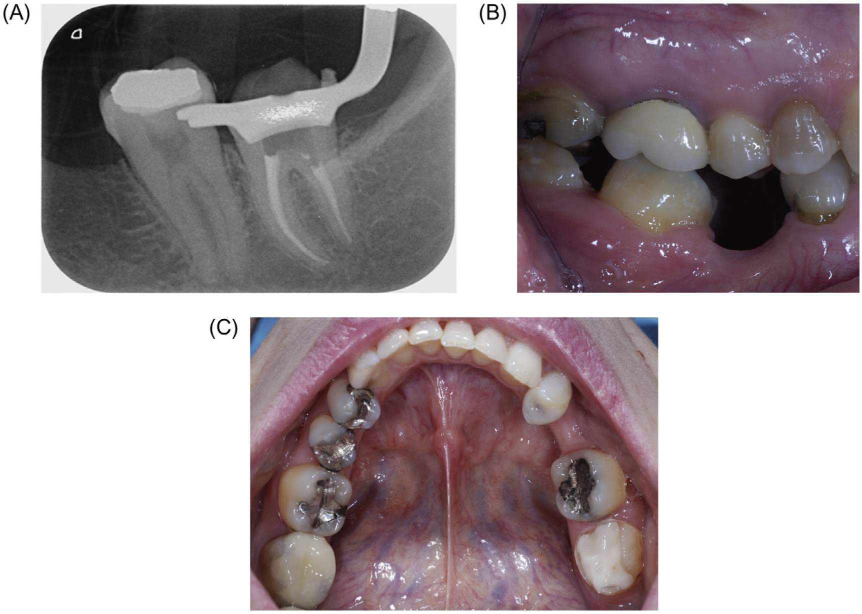

Figure 9.41 Preoperative situation: (A) radiograph; (B) lateral view; (C) occlusal view.

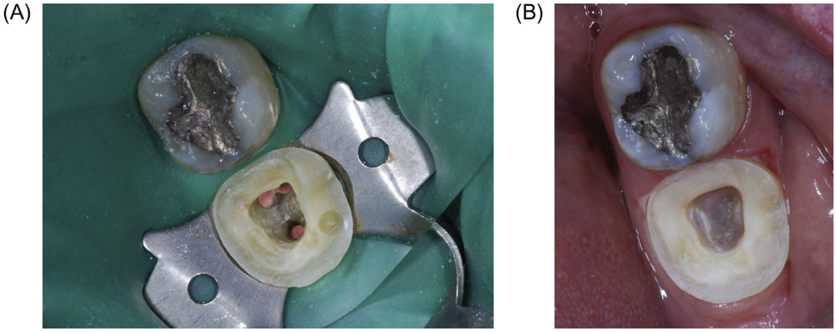

Figure 9.42 Per-operative situation: (A) endodontic access opening before sealing; (B) finished preparation after sealing the endodontic access opening with flowable composite.

way: the intaglio surface of the restoration was roughened by air particle abrasion with 50 μm alumina particles, subsequently the PFC-surface was cleaned with phosphoric acid gel and silanised (Clearfil Ceramic primer; Kuraray), while the semi-IPN-based resin matrix of the SFRC surface was reactivated for 5 min with a Bis-GMA-containing resin (Stick Resin; GC). The abutment tooth was sandblasted with 50 μm alumina particles in order to reactivate the adhesively sealed dentine. After selective enamel etching a one-step self-etch adhesive (Clearfil S3 bond plus; Kuraray) was applied to the entire tooth surface. The restoration was luted with a

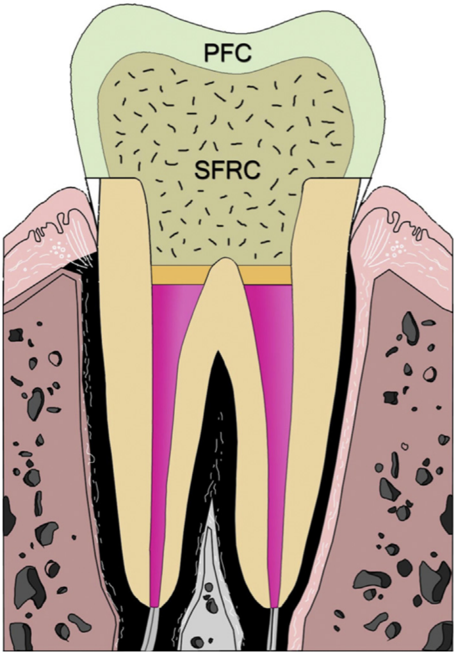

Figure 9.43 Schematic representation of a biomimetic resin composite endocrown.

dual-cure core build-up composite (Clearfil DC core plus; Kuraray). Occlusion and articulation were checked and adjusted after removal of the dental dam. The restorations were finished with fine-grit diamond burs, abrasive disks and strips and polished with rubber points and brushes (Fig. 9.45).

9.3 Conclusion and Future Trends

Clinical studies, after years of follow-up of indirectly or directly made large posterior composite restorations, have showed that fracture of the restoration was the most common reason for failure, with no significant differences between the two techniques. It was hypothesized that using SFRC substructures could reinforce the composite restoration for use in high stress-bearing areas of the dental arch. The function of the SFRC base is assumed to be based on supporting the superficial conventional composite and behaving as a crack arrest barrier, or in other words, to mimic the natural behavior of enamel and dentine. The present chapter briefly described the benefit of using SFRC in many clinical situations. Within the limitations of this case series of clinical indications, SFRC is a promising material that gives the clinician the opportunity to replace missing tooth tissue in a more biomimetic way. Therefore SFRC can be beneficial in large stress-bearing restorations as a dentine-replacing material, resulting in less fracture-related failures and improving

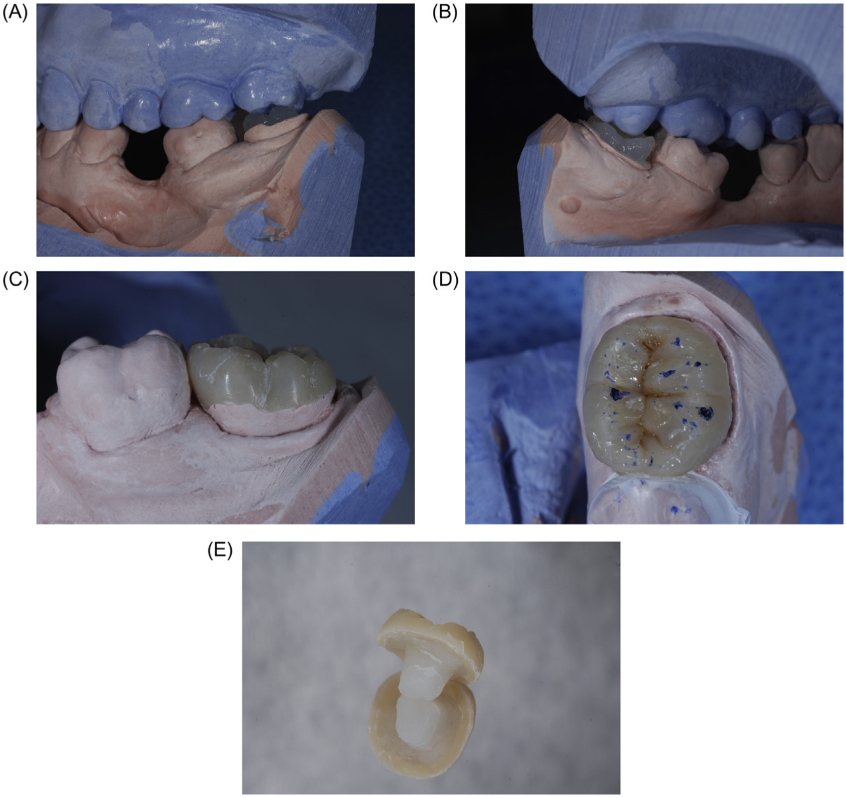

Figure 9.44 Fabrication of the endocrown: (A and B) dentine replaced by SFRC core; (C−E) biomimetic endocrown after veneering with enamel-replacing PFC.

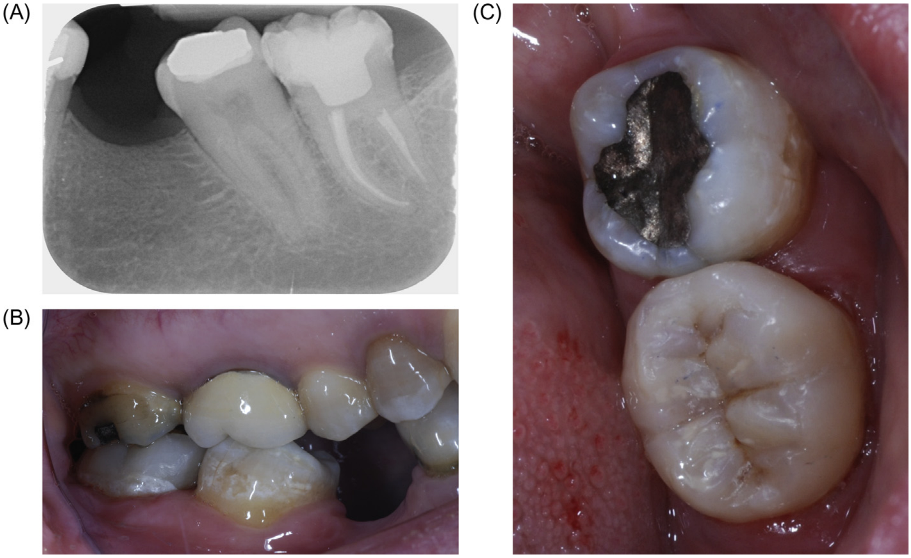

Figure 9.45 Post-operative situation: (A) radiograph; (B) lateral view; (C) occlusal view.

overall longevity of direct resin composite restorations. However, long-term clinical studies are currently in progress to determine the value and usefulness of using bilayered or biomimetic composite restorations made of a high toughness dentine-replacing SFRC, and a wear-resistant and highly esthetic PFC as enamel replacement in high stress-bearing areas.

Future developments in short fiber reinforcement technology are focused now on the optimization of the FRC CAD/CAM blocks, in order to have bilayered composite restorations. Attempts have been made to use a CAD/CAM system in the production of FRC restorations. There have been also efforts to use short fibers as part of the filler load within glass-ionomer cements, and some promising experimental materials are still under laboratory evaluation. Commercially available SFRC (everX Posterior; GC) contains millimeter-scale fibers, whereas the collagen fibers in dentine are of nanometer-scale ($\approx$50−500 nm thick and 23 μm long). Therefore, nanofibers can be a promising candidate as reinforcing material for dental composite, and might successfully mimic the natural structure and behavior of dentine, and perhaps improve the performance of dentine-replacing resin composite.

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Removable devices and facial epithesis prostheses

10

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Chapter Outline

10.1 Introduction to Removable Dentures: Key Requirements

Although fixed prosthodontics plays an important role in rehabilitation of partially edentulous jaws, there is still the need for conventional removable partial dentures and complete dentures. The majority of removable dentures are made from acrylic resin of polymethylmethacrylate (PMMA). The importance of using removable dentures will become even greater in the coming decades due to a progressive demographic ageing of the population with the need for transitional and long-term provisional prosthodontic devices. Age-related changes of the masticatory system include wear of teeth, loss of teeth, and changes of the oral mucosa and bone structures. All these are in relation to the capability of wearing removable dentures and

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to the potential technical failures of denture constructions due to changes in fit of the dentures and formation of stress concentrations in the denture, which can break the denture. Denture base and denture teeth resin materials will age and their physical properties change over time. This in combination with continuous dynamic loading conditions provokes denture failures, which are typically fatigue fractures of denture bases and loosening of denture teeth. Also impact types of denture failures may occur when the denture is accidentally dropped on a hard surface.

10.2 Removable Denture Failures

Damage to a denture can occur either outside or inside the oral cavity. In terms of intraoral damage, the oral environment affects the denture both chemically and mechanically. The water of saliva is absorbed into the polymer of denture base and it weakens the material by plasticizing the polymer. Mechanical stresses to the denture are caused by mastication and biting force, which are described in more detail in Part I of this book. A study of frequency and types of removable denture damage was undertaken which showed that one of the most typical types of failure was midline fracture of upper complete denture (Vallittu et al., 1993). A midline fracture of an upper complete denture runs through the notch between the two central teeth, extending partially or completely through the denture base. The upper complete denture and especially the interproximal area of central incisors are affected by extension due to tensile stress form the masticatory forces. While the denture base is deformed under the repeated loading, flexural fatigue failure of the denture base PMMA can occur. Clinical factors related to the failure of single dentures are: (1) improperly contoured mandibular occlusal plane, (2) high frenulum attachment, (3) occlusal scheme, (4) high occlusal forces, (5) denture foundation, and (6) thickness of the denture base (Farmer, 1983). It is important to note that the typical thickness of the denture base plate and the maximal biting forces of partially and especially totally edentulous patients do not enable denture fracture to occur by one single heavy biting cycle. Denture base fracture is a fatigue fracture of brittle denture base polymer of PMMA due to hundreds of thousands of biting cycles annually.

Removable partial dentures have more complex shape than complete dentures and therefore type of damage differs from that of complete dentures. Removable partial dentures may also contain thin denture base plate parts, which are prone to even static and especially dynamic loads and related fatigue fractures. Occasionally removable partial dentures are made of autopolymerizing (cold curing) denture base resins, which are known to have lower strength and poorer bonding to denture teeth, and therefore fractures and loosening of teeth occur more often with removable partial dentures than with complete dentures of heat-cured denture base polymer.

The commonest types of denture, which require repair by dental laboratory technicians, are upper complete dentures which have broken from the midline during mastication. This suggests that the failure mechanism is a fatigue failure, which has also been confirmed by fractographical analysis of the fracture surface of complete dentures (Vallittu, 1996a). Typically the upper complete denture fracture occurs

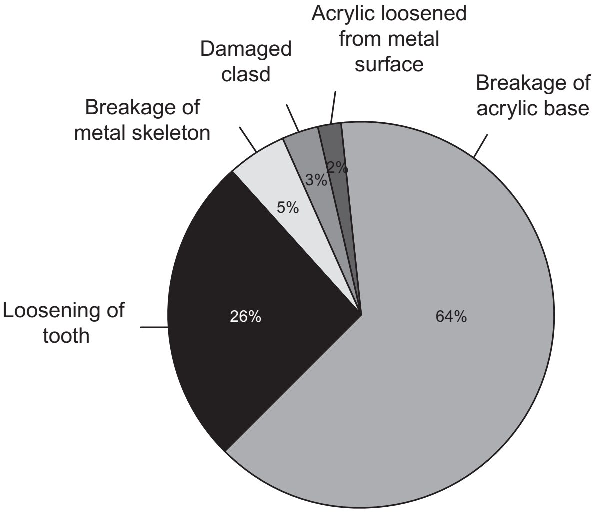

Figure 10.1 Types of failures of removable dentures needing repair (Vallittu et al., 1993).

after three years of use of the denture. Fig. 10.1 describes the distribution of types of denture failures requiring repair. Although the failure mechanism of fractures of acrylic resin based denture polymers is fatigue of the material, and progression of the fracture continues even with low level of stress, the magnitude of tensile stress affects velocity of the propagation of the fracture. Therefore, biting forces coming from the natural opposing teeth, which are obviously higher than of that from removable dentures, provoke and hasten the progress of denture fracture (Yli-Urpo et al., 1985). It is also worthy of mention that fractures initiate from surface flaws and surface cracks. Even minor defects of the denture base surface at the location of high tensile stress can dramatically lower the fatigue resistance of the denture (Vallittu et al., 1996b). Therefore more attention should be paid to finishing of denture bases in order to prolong the functional lifetime of the denture.

Damage to removable dentures is a frequent problem and it causes much distress and cost for patients. Therefore prevention of denture fractures by ensuring high quality of finish for the material surface, correct dimensioning of the dentures, and selection of the most effective type of denture base reinforcement, are key factors in the elimination of fractures of dentures.

10.3 Repair of Denture Failures: Treatment of Fracture Surface and Denture Teeth

Fractures of denture base polymer need to be repaired frequently in dental laboratories. Repair process of denture base polymer, which is basically non-cross-linked PMMA, follows the commonly used process of adding autopolymerized denture base resin (repair resin) to the repair sites of the denture. Before curing the autpolymerized resin, monomers dissolve and swell the fracture surface of the dentures and result information of secondary IPN bonding of the repair resin, which has be described more in detail in Part I of this book. A special feature which relates to the durability of repair of denture base is the wetting time of the fracture surface with monomer liquid of methyl methacrylate (MMA) of the repair resin prior curing the repair resin in water at elevated temperature. It has been shown that prolonging the wetting time of the fracture surface from 5 to 180 seconds increases the repair strength considerably. By prolonging the wetting time with monomer liquid, the bonding of the repair resin to the fractured denture acrylic is improved and the interfacial failure type of repair resin to the old polymer changes to be more cohesive than adhesive. If the surface wetting time by monomer liquid is too short, the repaired area will likely fail by adhesive type failure of the repair resin from the old acrylic resin (Vallittu et al., 1994a). Microscopic examination of the surface of denture PMMA has shown that visual dissolving of the denture base PMMA begins after 30−60 seconds wetting time with the MMA monomer liquid. The relationship between dissolving depth (diffusion depth of monomers) and the surface wetting time is linear (Vallittu, 1995a; Vallittu and Ruyter, 1997a).

A similar mechanism of secondary IPN bonding exists between denture base polymer and resin denture tooth. Resin denture teeth have ridge lap surface with certain parts of non-cross-linked polymer, which are the locations where the secondary IPN bonding can take place. It is known that heat curing denture base resins bond better to the denture teeth than autopolymerized (cold curing) denture base resins. This is due to the fact the by increasing the temperature, diffusion of monomers to the denture teeth increases and the thickness of the secondary IPN layer, which is responsible for the bonding, increases as well (Vallittu and Ruyter, 1997b). There is a nonlinear relationship between depth of diffusion of monomers to the polymer and curing temperature, which means that by increasing the curing temperature the secondary IPN bonding becomes stronger. The thickness of the secondary IPN layer between denture teeth and denture base polymer is around 10 mm, which can be obtained at curing temperatures of autopolymerized denture base resin of 55°C or above. Lower curing temperatures of autopolymerized denture base resin result in poor bonding and risk of adhesive failures between denture teeth and denture base polymer. Curing temperature of heat-cured denture base polymer at 100°C enables proper diffusion on monomers to the surface denture teeth and forms durable secondary IPN bonding. However, it is obvious that in the case of both autopolymerized and heat-cured denture base resins the bonding surface of denture teeth have to be free from contamination of wax and plaster isolation agents.

10.4 Reinforcing Denture Bases With Metal Wires

Numerous investigations have been performed to compare the effects of metal wires and meshes to the static flexural strength of denture base resin. Surface treatments (mechanical and chemical) of metal wires and mesh in order to improve bonding and load transfer from polymer to metal have also been investigated, and only a limited effect of the surface roughness on the static strength of the denture base polymer was found (Vallittu and Lassila, 1992a,b). It has been concluded that by selecting highly rigid type of metal which is incorporated into the denture base polymer, flexural strength of the denture base polymer can be increased, whereas metal wires, even after surface modifications, have only a limited effect on the strength and load-bearing capacity of the denture base polymer (Vallittu, 1995b).

As it has been discussed earlier in this chapter, failures of denture base plates are most often caused be repeated loading and fatigue of the material. When the denture base plate with metal wire inclusion is subjected to dynamic loading, the effect of metal wires become even less and therefore metal inclusions in order to increase the strength of the material have not been shown to be of practical value (Vallittu et al., 1994b, 1994c). The benefit of metal wire and mesh inclusions are that the metal holds the fractured pieces of acrylic together until the metal wire fails by itself due to fatigue.

10.5 Reinforcement of Dentures With FRC

Reinforcing fibers, i.e., use of fiber-reinforced composites (FRC), have been tested to solve the problem of fractured denture base polymers since the early 1960s (Smith, 1961; Hargreaves, 1969; Schreiber, 1971). Function and theory behind fiber reinforcement and FRC material to reinforce polymers has been described in Part I of this book. With regards to reinforce denture bases, one needs to distinguish between two approaches to reinforced denture bases. One is based on total fiber reinforcement (TFR) where the entire denture base plate is reinforced with fibers. This approach was described by Ladizesky with the use of polyethylene fibers (Ladizesky and Chow, 1990). Although this approach effectively reinforced the material it faced clinical problems of protruding fibers and difficulties in polishing the denture surface. The TFR approach has not therefore been adopted for clinical use. Another approach, described by Vallittu and Lassila (1992a,b), was based on reinforcing only the weakest part of the denture with precisely placed and oriented fibers. This approach is called partial fiber reinforcement (PFR). Successful use of this approach requires information about the existing or supposed path of the fracture line. When dentures are repaired, the fracture line and corresponding correct position of PFR can easily been determined. In the case of reinforcing the denture during its fabrication, the position and orientation of the fibers have to be estimated based on the knowledge of the fractures of the dentures. Clinical follow-up studies of the function of PFR made of PMMA preimpregnated glass fiber reinforcements in complete and partial removable dentures have shown effectiveness of the PFR (Narva et al., 2001) (Fig. 10.2).

As described in the Part I (Chapter 3: Structural properties of dental FRC structures) of this book, the positioning of fiber reinforcement to the denture base is

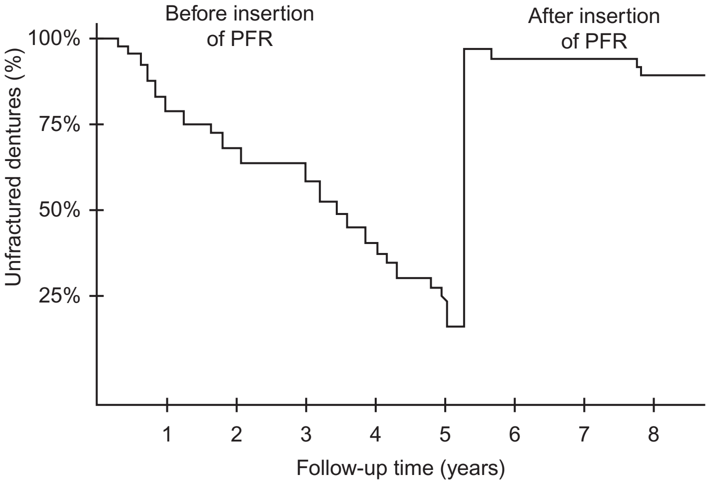

Figure 10.2 Survival curves of dentures of problematic history with recurrent acrylic fractures and the survival of the same dentures after insertion of partial fiber reinforcement (PFR) of PMMA preimpregnated glass fibers.
Modified from Narva, K., Vallittu, P.K., Yli-Urpo, A., 2001. Clinical survey of acrylic resin removable denture repairs with glass-fiber reinforcement. Int. J. Prosthodont. 14, 219–224.

important for the reinforcing effect. Fibers should be placed in the region of denture base where the highest tensile stresses are occurring and orientation of fibers should be perpendicular to the direction of the fracture line. Optimal reinforcing effect can be obtained by using continuous unidirectional fibers (Stick, GC, Japan). A typical example for using continuous unidirectional fibers is in elimination of midline fractures of upper complete dentures with "horse shoe" shaped fiber reinforcement, which is placed as close to the ridge lap surface of anterior denture teeth as possible. Fiber reinforcement should extend to the region of premolars. Another type of denture where unidirectional fibers can be used effectively is the lower removable partial denture.

If the direction of the fracture line is not known or cannot be predicted, the most suitable reinforcement type is bidirectional woven fiber reinforcement (StickNet, GC, Japan). Due to lower Krenchel's factor of woven fiber reinforcement compared to unidirectional fibers, the ultimate improvement in strength is less than with unidirectional fibers but the reinforcing effect is available in several directions. Typical types of dentures which benefit from woven fiber reinforcement are upper removable partial dentures and implant retained overdentures.

In the optimal case the polymer matrix within the fiber reinforcement is the same as used in the denture base plate, namely PMMA. In order to have well wetted and properly impregnated fiber reinforcement with denture base PMMA of high viscosity, the PMMA preimpregnated fiber reinforcements should be used (Stick and StickNet, GC, Japan). By using PMMA preimpregnated fibers, there will be similar polymer matrix between the glass fibers and in the entire denture base.

This has been shown to provide the highest possible reinforcing effect against the fatigue failures, but somewhat lower effect against static load (Narva et al., 2005a, 2005b). The difference between dynamic and static strength comes from the distribution of fibers and inter-fiber distance of reinforcing fibers. Other types of fibers including polyethylene fibers and ribbons do not reinforce denture base polymers. It is essential to differentiate between types of linear, semi-IPN and cross-linked polymer matrix of fiber reinforcement. Purely cross-linked polymer matrix of fiber reinforcement cannot be used with denture base PMMA because cross-linked polymer matrix does not bond to the denture base polymer. If the fiber reinforcement contains semi-IPN polymer matrix (everStick, everStickNet, GC, Japan) (see Part I), or is of compatible non-cross-linked polymer, i.e., dissolvable with MMA, bonding of the denture base resin to the fiber reinforcement can be obtained through the secondary IPN bonding mechanism. If semi-IPN polymer matrix fiber reinforcement (everStick, everStickNet, GC, Japan) is used, the light cured fiber reinforcement has to be wetted with the monomer liquid of denture base acrylic for a period of three to five minutes, after which the reinforcement is inserted into the denture base resin (heat-curing or autopolymerizing). After polymerization of the denture base resin, there will be secondary IPN bonding between the fiber reinforcement and denture base polymer. There has been discussion of using silane promoted bonding of exposed glass fibers of the fiber reinforcement and the denture base resin instead of secondary IPN bonding between polymer matrix of fiber reinforcement and denture base polymer. Due to poor hydrolytic stability of low temperature silane promoted adhesion it cannot be used as a primary mechanism of bonding between the fiber reinforcement and denture base polymer. Thus, the only reliable and stable bonding mechanism is obtained between polymer matrix of reinforcement and denture base resin by the secondary IPN bonding.

When the glass fiber reinforced denture base is visually examined in the quality control process before releasing the denture from the laboratory, the fiber reinforcement should be visible only in translucent light without showing any white areas, which can exist if the fiber reinforcement has not been completely wetted and impregnated with acrylic resin. If there are white areas, or the reinforcement is not located at the margins of the denture where the fracture most likely will begin, the reinforcing effect of the fiber reinforcement is not optimal.

10.6 Technical Use of FRC Reinforcement in Removable Dentures

In reinforcing dentures during fabrication or repair, glass fiber reinforcements with preimpregnation polymer of PMMA (Stick and StickNet, GC, Japan) or light curing semi-IPN impregnation resin (everStick and everStickNet, GC, Japan) are used. In the following step-by-step figures, an upper partial denture (Fig. 10.3A–L), upper complete denture (Fig. 10.4A–F), and lower partial denture (Fig. 10.5A–G) are reinforced during denture fabrication with PMMA preimpregnated PFR.

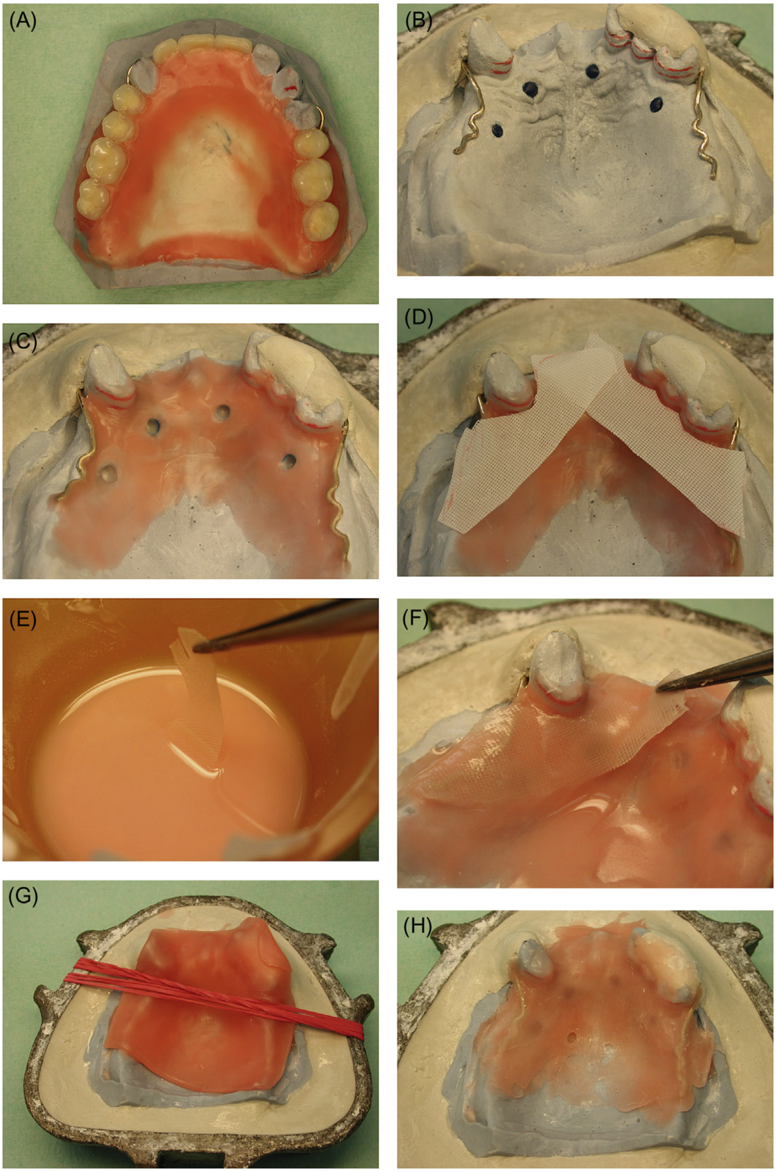

Figure 10.3 Using partial fiber reinforcement (PFR) in fabrication of an upper removable partial denture. (A) Upper partial denture in wax. (B) Positioning holes for the PFR are marked. (C) Wax spacer for the PFR is made. (D) PMMA preimpregnated reinforcements (StickNet) are cut. (E) Fiber reinforcements are wetted with the cold-curing acrylic resin. (F) Fiber reinforcements are placed on cast. (G) Fiber reinforcements are covered with form-giving wax plate. (H) Fiber reinforcement has been cured in water bath. (I) Fiber reinforcement has been shaped. (J) Fiber reinforcement is packed into heat-curing resin dough. (K) Heat-curing resin is compressed and cured. (L) In the finished denture fiber reinforcement is visible in translucent light without any signs of poorly impregnated (*white*) areas. Fibers are placed close to the margins of denture where the fracture may begin.

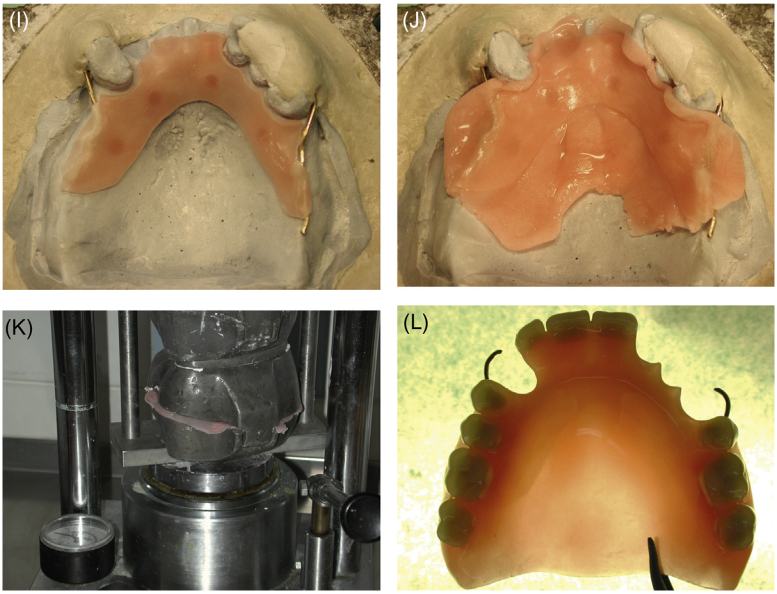

Figure 10.3 (Continued)

10.7 Introduction to Facial Prostheses: Key Requirements

Organ defects in the facial region, such as congenital defects, or acquired conditions as a result of trauma or tumor surgery, can be restored either by reconstructive and microvascular surgery, or by a prosthesis. In treating these patients, a multidisciplinary approach is preferred. Modern plastic surgery has made it possible to reconstruct large hard and soft tissue defects by using microvascular flaps and bone grafts (Thiele et al., 2015). However, surgical reconstruction of a facial defect is a complicated procedure and it usually requires several operations to achieve a good result (Ariani et al., 2013). The reconstruction is dependent on the availability of autogenous bone grafts, and both allografts and xenografts have been used as bone substitutes (Ayoub and Al-Fotawei, 2015). However, the new innovative surgical techniques do still have limitations, and in some cases the prosthetic reconstruction is the only possibility to rehabilitate the patient. The purpose of the prosthesis is to restore the normal anatomy and substitute for the missing structure, such as an ear, the nose, an eye, or a larger part of the face, and it is of great psychological importance for the patient (Beumer et al., 2011, Mantri and Khan, 2012, Nemli et al., 2013, Toso et al., 2015, Wondergem et al., 2015). In some cases, the reconstruction of a large facial defect consists of both microvascular tissue transfer and an epithesis (Mueller et al., 2015).

Today, the facial prosthesis, or epithesis, is retained within the surrounding facial structures by adhesives or implants (Ethunandan et al., 2010, Thiele et al., 2015). An implant-retained facial prosthesis is usually considered to be the optimum type

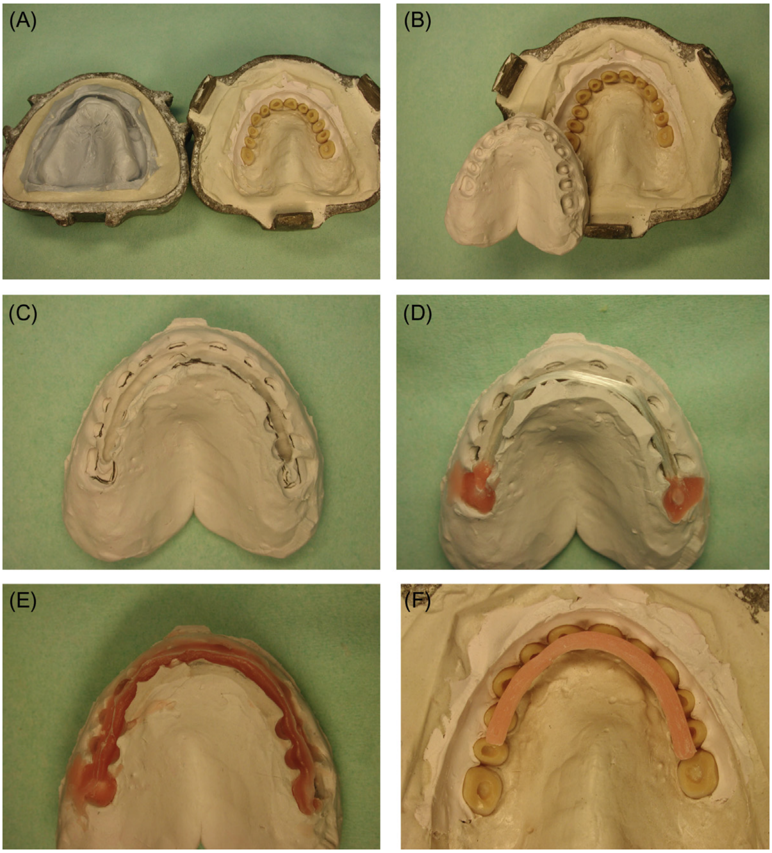

Figure 10.4 Using partial fiber reinforcement (PFR) in fabrication of an upper complete denture. (A) Upper complete denture teeth in mold. (B) Putty silicone is compressed into the space of acrylic resin. (C) A groove for the PFR is made in the putty silicone. (D) PMMA preimpregnated reinforcement (Stick, GC, Japan) is placed into the groove. (E) Reinforcement is wetted with cold-curing resin and cured. (F) PFR is ready to be packed into the heat-curing resin. Fibers are placed close to the ridge lap surface of denture teeth which is the location of the potential starting area of fracture.

of prosthesis. The implants are anchored to the facial bone and function as a fixation platform for the prosthesis. Good retention is important for both functional and esthetic reasons, as a good marginal fit makes the prosthesis look more natural and less visible. For psychological reasons it is, of course, important for the patient that the prosthesis is stable. An implant-retained prosthesis makes the patient feel more self-conscious in comparison to an adhesive-retained prosthesis. Overall, studies show that implant retained prostheses enhance quality of life (QOL) among those patients who have received prosthodontic rehabilitation, and the prostheses are generally considered highly satisfactory (Ariani et al., 2013, Nemli et al., 2013, Wondergem et al., 2015). The patients tend to be more satisfied with auricular

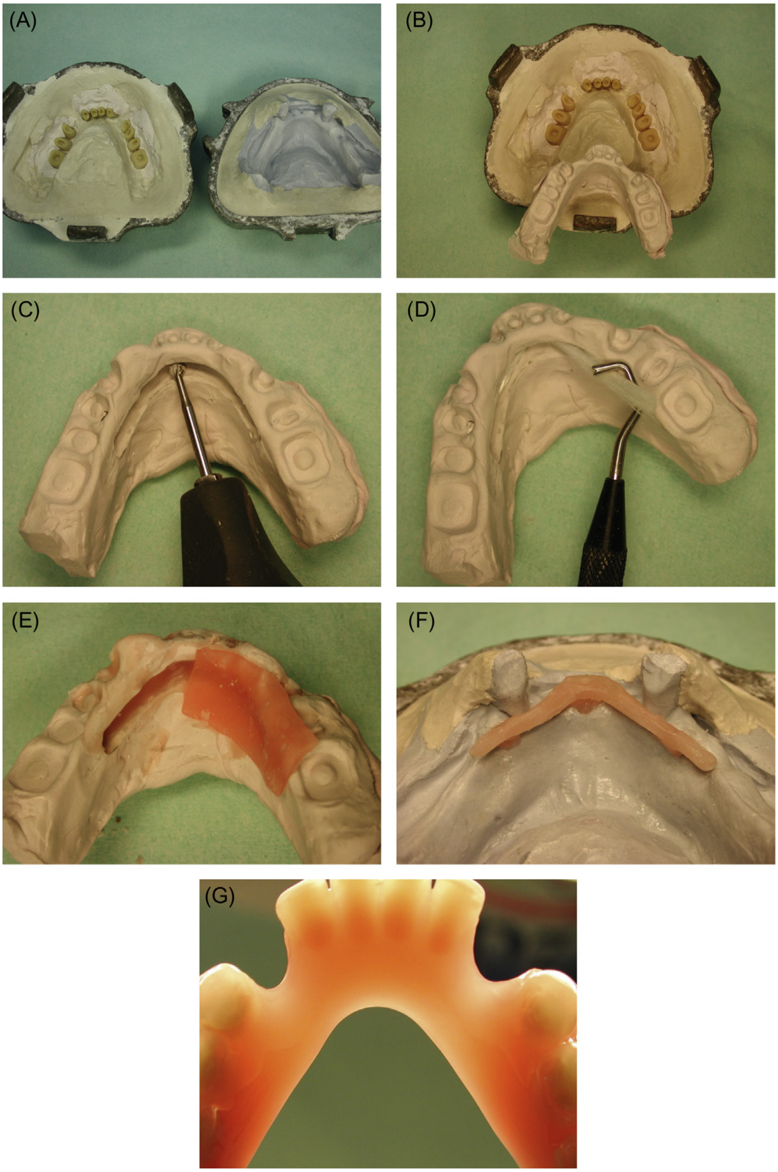

Figure 10.5 Using partial fiber reinforcement (PFR) in fabrication of an upper complete denture. (A) Lower partial denture teeth in mold. (B) Putty silicone is compressed into the space of acrylic resin. (C) A groove for the PFR is made in the putty silicone. (D) PMMA preimpregnated reinforcement (Stick, GC, Japan) is placed into the groove. (E) Reinforcement is wetted with cold-curing resin, covered with the form-giving wax plate and cured. (F) PFR is ready to be packed into the heat-curing resin. (G) Finished denture with glass PFR in translucent light without any white areas of poorly wetted and impregnated fibers. Fibers are placed close to the denture margin where the fracture may begin.

prostheses than with nose and orbital prostheses. This has to do with the condition of the tissue surrounding the defect, how comfortable the prosthesis is to wear, the accuracy of the esthetic details (form, color) and, of course, the retention of the prosthesis. Orbital and nose prostheses may be the most challenging kinds of prostheses to fabricate, regarding both esthetics and comfort (Smolarz-Wojnowska et al., 2014). For a large mid-facial defect three or four implants are needed, while one or two implants is the minimum requirement for an ear prosthesis. The aim is to place the implants in good quality bone, where the prognosis of the implants is the best. In the facial region the implant surgery is usually done in two stages, and after 4−6 months of osseointegration the abutments and attachments are attached to the implants (Woolfardt et al., 2003, Goiato et al., 2012).

There are several requirements for the materials used to fabricate a facial prosthesis, as the prosthesis should have many different qualities to be both functionally and esthetically successful. The prosthesis has to be durable, flexible, and lightweight, and it should, of course, have esthetic qualities of looking as natural as possible in recreating the lost structures of the face. The material should also have good patient-accommodation properties: it should be nontoxic and nonallergenic, and it has to feel comfortable against the facial structures. It is also important that the material is easy to process and that it has good mechanical characteristics. It has to be durable, but soft enough to comfortably adapt to the surrounding structures, and it should be resistant to environmental factors, such as light and chemicals (Chalian et al., 1972, Sweeney et al., 1972, Lontz, 1990).

During history, many different materials have been used for replacing missing parts of the face: cloth, waxes, resins, wood, gold, and silver. Vulcanite rubber was introduced by Upham in 1901. This material was replaced by acrylic resin (PMMA) in the early 1940s. Today it is still commonly used for intraoral, removable dentures. PMMA is durable and easy to process, but it is a hard and nonelastic material, which can make it uncomfortable in a facial prosthesis as it is in direct contact with the facial tissue (Heller and McKinstry, 1995, Lemon et al., 2005, Beumer et al., 2011). Today, most facial prostheses are made of medical grade silicone elastomer, a room-temperature vulcanizing polymer based on polydimethylsiloxane. The silicone elastomers have been widely studied regarding mechanical and esthetic properties (Lai et al., 2002, Begum et al., 2011, Hatamleh et al., 2015) and as the materials have improved over the years, the mechanical properties are considered to be adequate. However, a silicone facial prosthesis still has to be remade every 1.5−2 years, most often because of discoloration, which is due to environmental factors, such as ultraviolet light and chemicals (Visser et al., 2008, Hatamleh et al., 2010, Hatamleh and Watts, 2011).

10.8 Components of Facial Prostheses

A facial prosthesis consists of three major components:

- The major and visible part of the prosthesis which replaces the soft tissues, usually made of silicone elastomer.

- A rigid substructure or framework, which supports the soft silicone and to which the retention parts are incorporated. This has conventionally been made of PMMA, but in the following examples of this chapter, the framework has been fabricated from FRC material, which has several advantages compared to the heavy and structurally rigid PMMA.
- The retentive elements attached on the patient and to the prostheses.

There are different retention systems to fixate the prosthesis to the implants in the facial bone (Mantri and Khan, 2012, Thiele et al., 2015, Wondergem et al., 2015). These prosthetic attachments can be *magnets*, one part on the adverse surface of the prosthesis and the other part on the implant; or *clips* on the prosthesis' surface, attaching to a bar construction between two or several implants; or the prosthesis can be directly attached to the implant by a *precision attachment*. The attachments on the reverse surface of the prosthesis need a "clip carrier" material for the prosthetic attachments to attach to the flexible and soft silicone. Until now, acrylic resin has been the most used clip carrier material for the prosthetic retention elements. However, because of the different chemical structure of the silicone elastomer and the acrylic resin (PMMA), the bonding between these two materials is not very strong. As a result of this, one of the most usual failures of a facial prosthesis is that the acrylic resin gets loose from the silicone basis of the prosthesis. In larger facial prostheses the acrylic resin makes the prosthesis stiff, and heavy, and uncomfortable to wear. A loosened (de-bonded) acrylic clip carrier may be difficult to re-bond to the silicone surface.

Continuous unidirectional glass FRC has been suggested to be used as clip carrier material and framework in silicone facial prostheses (Kurunmäki et al., 2008, Kantola et al., 2011). FRC has many advantages compared to PMMA: the material is lightweight and it is possible to design a slightly flexible framework for a silicone prosthesis. The framework is, at the same time, constructed to serve as the clip carrier for the special attachments. Further, the bond strength between FRC and silicone elastomer is considered to be sufficient (Kantola et al., 2013, 2015). The flexibility of the FRC framework makes the margins of the silicone prosthesis fit tightly to the skin without affecting the skin negatively (Kantola et al., 2014). It is also possible to repair the FRC framework if there is a need to correct and tighten the margins of the prosthesis.

10.9 Manual Fabrication of a Fiber-Reinforced Composite Framework for a Silicone Elastomer Facial Prosthesis

The purpose of the FRC framework in a silicone facial prosthesis is to serve as a mechanical support for the soft silicone elastomer. It should enhance the marginal fit of the prosthesis, stabilizing the soft and thin silicone margins tightly to the skin. As a carrier for the fixation attachments, as magnets or clips, the framework has to be rigid enough to make all of the attachments fit to the corresponding attachments of the implants. The framework should be designed to give slight pressure to the

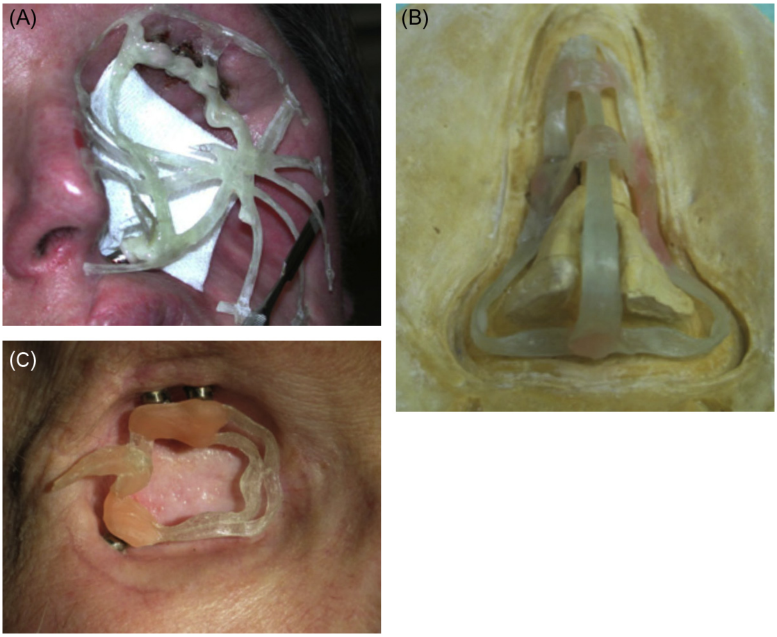

Figure 10.6 Examples of continuous unidirectional glass FRC frameworks: (A) large facial prosthesis; (B) nose prosthesis; (C) orbital prosthesis.

skin under the margins of the prosthesis. This is possible because of the elasticity of the framework when it is designed with long extensions, ending at the margins of the prosthesis. This design will help the prosthesis to fit tightly to the skin during facial expressions and jaw movements. Fig. 10.6A–C shows examples of FRC frameworks of facial prosthesis (Fig. 10.6A–C).

The framework should be individually planned for each patient, depending on the form, quality, and size of the facial defect. The framework is a substitute for the lost, natural skeletal support of the soft tissues. Planning and fabrication of the FRC framework and including bonding the fixation elements (clips, magnets) are made on plaster model (Fig. 10.7). As the FRC framework functions as carrier of the retentive elements (clips, magnets), it should be rigid enough to withstand the mechanical forces that are due to repetitive removal of the prosthesis from the attachments. In some cases the prosthesis is attached to eye-glasses.

10.10 Manual Fabrication of Facial Prostheses on Plaster Model

The FRC framework is shaped between the magnets and is attached to the magnets by using autopolymerized acrylic resin or flowable resin composite. The framework

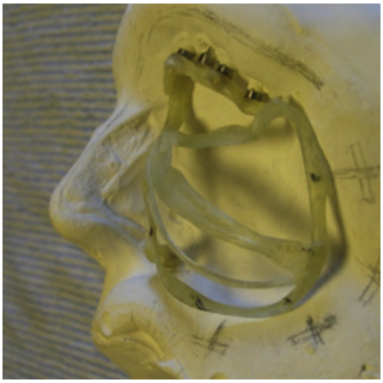

Figure 10.7 Planning and fabrication of the glass FRC framework is made on plaster model. Special emphasis is put on receiving slight compression of the margins of the prosthesis to the adjacent soft tissues by FRC "legs", which are marked to the model.

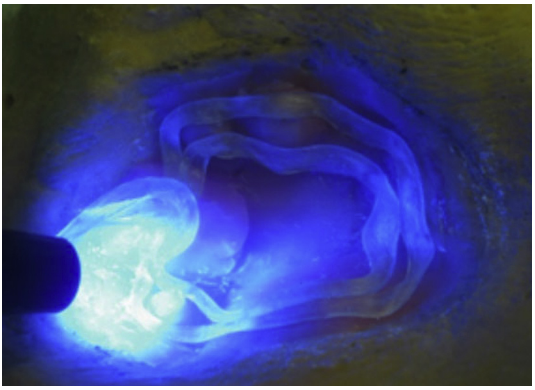

Figure 10.8 FRC framework is initially light-cured by hand-held light-curing device and post-cured in a light-curing oven.

is light-cured according to the manufacturer's instructions for 2 × 40 seconds using a hand-held light-polymerizing unit and then postcured polymerized in a light-polymerizing oven (Fig. 10.8).

The shape of the facial prosthesis is sculpted in wax on the FRC framework (e.g., Toughened Modelling Wax; Wright Cottrell and Modelling Wax for epithetics; Bredent) on the plaster model. The wax-up is tried on the patient (Fig. 10.9A and B). The shape of the wax-up and the shape, size, and quality of the defect determines the design of the FRC framework, as the design is planned to support the silicone and, if needed, the margins of the prosthesis. The framework should have adequate stiffness between the magnets. The amount, length, and direction of the fibers determine the flexibility of the framework and the amount of pressure on the skin at the margins of the prosthesis.

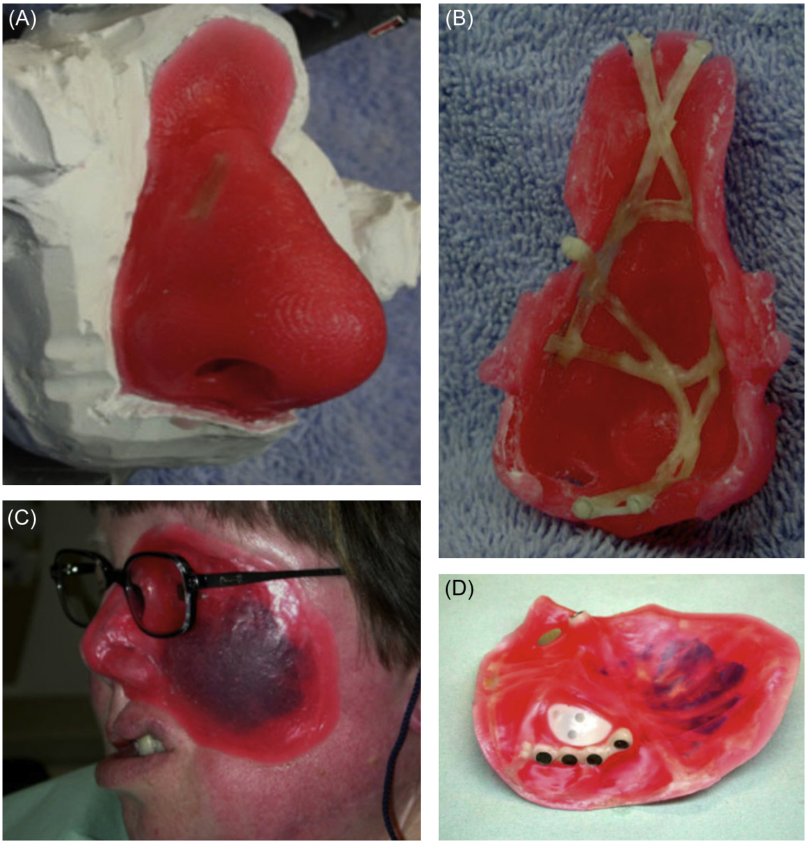

Figure 10.9 Testing of wax-ups on patient: (A) nose prosthesis from outside; (B) nose prosthesis from inside; (C) facial prosthesis from outside; (D) facial prosthesis from inside.

The areas, which need support or elasticity from the framework, are marked on the wax-up. After shaping the outer surface of the wax-up, the inner surface and the thickness of the wax layer is determined. Furrows for the FRC framework are carved in the inner surface of the wax. The wax up is tried on the cast and the magnets (e.g., Prosthesis Mini and Midi Lip Magnets; Technovent Ltd), which are attached to the implant replicas on the cast. The FRC framework of fiber bundles (everStick C & B, GC, Japan) is shaped according to the furrows in the wax. In designing larger FRC frameworks, two fiber bundles can be attached to each other to get a framework stiff enough. The fiber bundles are strengthened with flowable resin composite. The terminal ends of the fiber bundles are made T-shaped to reinforce the edges of the prosthesis and to make the endings act as “springs” to keep the edges in place against the skin. The magnets are prepared with airborne-particle abrasion (Rocatec, Espesil, grain size 110 μm) to enhance the bonding of the metal surface to the FRC bundle. If the layer of silicone elastomer is thin at the site of the magnet, the metal colored magnet can be covered with a thin layer of opaque skin colored paint.

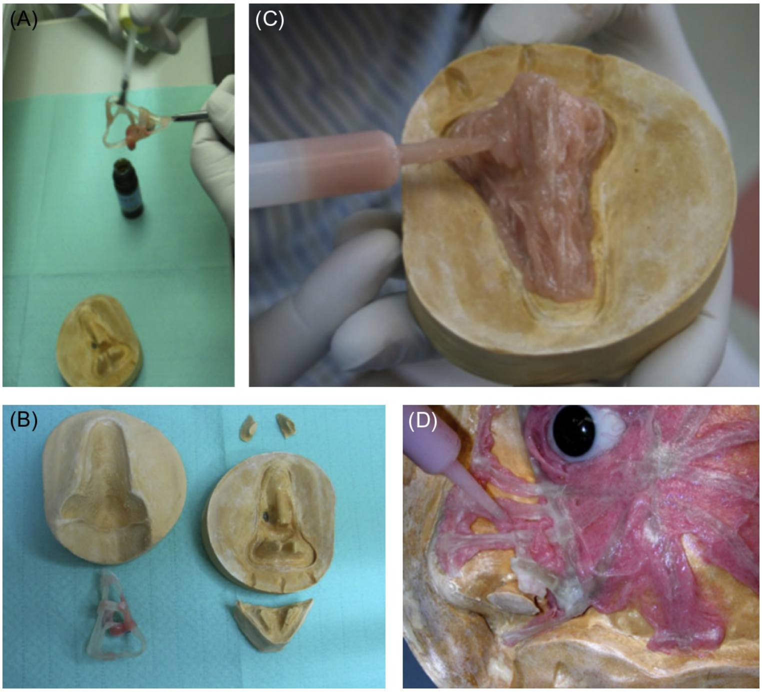

Figure 10.10 (A) After cleaning, the FRC framework the framework is primed, and (B)−(D) veneering the framework with silicone elastomer on plaster model.

The stone mode and the FRC framework are cleaned and wiped with acetone to remove possible dust and grease. A primer (e.g., Gold Platinum Primer A-330-G; Factor II) is applied to the entire FRC framework. The base and catalyst of the silicone elastomer (e.g., MDX4-4210; Dow Corning) is mixed manually, adding color pigments and Rayon Fibre (Factor II) matching the skin shade of the patient. The silicone is applied into the stone mold (Fig. 10.10A−D). The silicone is heat polymerized in an oven for 2 hours, at 90°C. Finished nose and facial prostheses are presented in Fig. 10.11A and B.

10.11 Future Trends

Removable dentures will be used in prosthetic rehabilitation also in the future. There have been initiatives to change the fabrication process from manual wax-up and molding technique to CAD/CAM process. Utilization of CAD/CAM processes is challenging due to resiliency of oral mucosa. On the other hand, some improvements in denture base polymers may also take place. There is ongoing research to evaluate various thermoplastic injection molding polymers as denture base material (Hamanaka et al., 2014). Interests have also been paid to the studies for improving

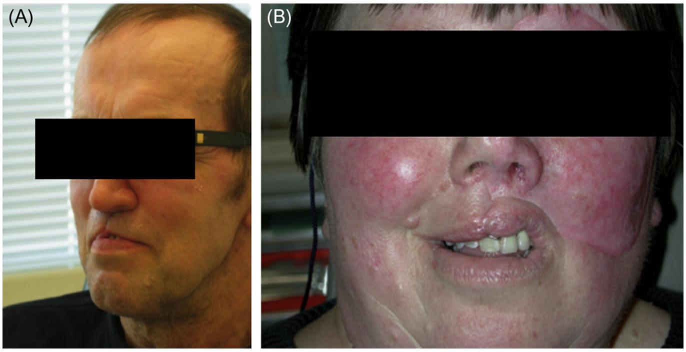

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Figure 10.11 (A) Finished nose prosthesis, and (B) facial prosthesis.

cross-linking systems of conventional powder-liquid type acrylic resins (Kawaguchi et al., 2014).

The surgical techniques used in craniofacial reconstruction are constantly developing. Autologous bone is in most cases the best option. However, the supply of autologous bone is limited, and a surgical reconstruction of the face requires a certain type or shape of bone. Autologous bone grafting means more surgical procedures and morbidity of the donor site. Because of this, biomaterials have been developed to replace the use of natural bone. The biomaterials may either be biologically active materials, used as matrices for tissue formation, or inert implant materials used to replace craniofacial bone. Biomaterials, in combination with tissue engineering, are one of the surgical rehabilitation options that most probably will be more common in the future. Even facial transplants have been performed, but this procedure is extremely complicated, and is certainly not suited as a routine surgical rehabilitation of any facial defect.

Even if the mechanical properties of the maxillofacial silicones are considered adequate, one large problem is still the rapid aging of the material. Because of the degradation of the silicone and the discoloration of the prosthesis' surface, a facial prosthesis usually has to be remade every 1.5−2 years. This degradation has to do with exposure to external environmental factors, such as ultraviolet light, and may also be due to a microbacterial film consisting of yeast and bacteria species on the surface of the prosthesis which is in contact with the skin (Visser et al., 2008, Ariani et al. 2012). These properties of the maxillofacial silicone elastomers should be enhanced. Studies are ongoing to improve the color stability by using different kinds of UV-absorbers, such as opacifiers and nano-oxides.

The use of advanced technology in the fabrication process of facial prostheses is gradually making the role of manual, artistic work even smaller. Advanced digital biotechnology can be used in different steps during designing or fabricating a facial prosthesis. Today it is already possible to combine manual, artistic design in certain steps of the fabrication with the use of digital technology in other steps. In the future, the use of scanning technology, modeling software, and computer-aided manufacturing will probably reduce the costs and the fabrication time of facial prostheses, and it might also lead to the development of new materials for facial prostheses.

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Orthodontic retainers

11

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Chapter Outline

11.1 Introduction to the Retainers

Retention is an essential phase of orthodontic treatment in order to maintain the correct alignment obtained after active tooth movement. Used since the 19th century, it is the only way to maintain post-treatment results, even if eminent Authors are in disagreement with this principle. Edward Angle, for example, was confident that occlusal forces on teeth in normal occlusion would maintain them in their position (Booth et al., 2008). On the contrary, Case stated that stable intercuspidation, even if compulsory, is not sufficient for stability (Case, 2003). The main causes of post treatment relapse can be classified in dental factors, including primary tooth loss, size of the teeth crowns, and intra-bone position of the tooth germ; periodontal factors, first of all inflammation and rebound effect; musculoskeletal factors, referring in particular to neuromuscular imbalances and leftover jaws growth; and general factors: age, sex, and ethnical group (Stanaitytė, 2014). Despite appearances, the real cause of relapse is largely unknown (Tanaka et al., 2005). However, many authors have attempted to rationalize the problem clustering the different variables involved (Bearn, 1995): teeth moved through bone by orthodontic appliances often have a tendency to return to their former positions. Bone and adjacent tissues have to be allowed time to reorganize after treatment; Arch forms, particularly

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mandibular, cannot be permanently altered by appliance therapy. For this reason using a retainer of the lower jaw seems essential.

The most current edition of The Glossary of Prosthodontic Terms defines a splint as "a rigid or flexible device that maintains in position a displaced or movable part; also used to keep in place and protect an injured part". A secondary definition of splint used in this glossary is "a rigid or flexible material used to protect, immobilize, or restrict motion in a part" (The Academy of Prosthodontics, 1999).

11.2 Materials Used in the Retainers

The choice between the fixed (Fig. 11.1) and removable (Fig. 11.2) retainer should consider different aspects: the fixed one is generally preferred when there is a high risk of relapse, and because it is free from patients' compliance (Tacken et al., 2010). The most common fixed retention device is the canine-to-canine retainer bonded to anterior teeth. Lee (1981) considered the following indications: severe pretreatment lower incisor crowding or rotation; after increase in the lower intercanine width; after advancement of the lower incisors during active treatment; after non-extraction treatment in mildly crowded cases; after correction of deep overbite.

Moreover, Zachrisson (1983) stated following indications for the flexible wire retainer: closed median diastemas; spaced anterior teeth; adult cases with potential postorthodontic tooth migration; accidental loss of maxillary incisors, requiring closure, and retention of large anterior spaces; spacing reopening, after mandibular incisor extractions; severely rotated maxillary incisors; palatally impacted canines.

The retainers bonded only onto two canines (Drawing 11.1—PROPOSAL—to be modified by Office), clearly effective for the maintenance of post-treatment intercanine width, are generally unsatisfactory for preventing vestibularization and incisal rotation. Conversely, metallic wire retainers (Drawing 11.2—PROPOSAL—to

Figure 11.1 Fixed retainer.

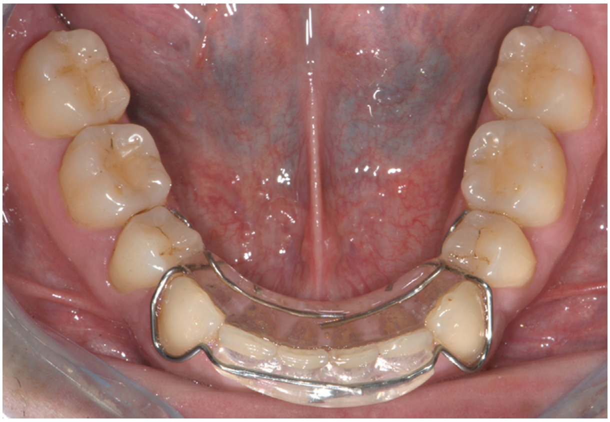
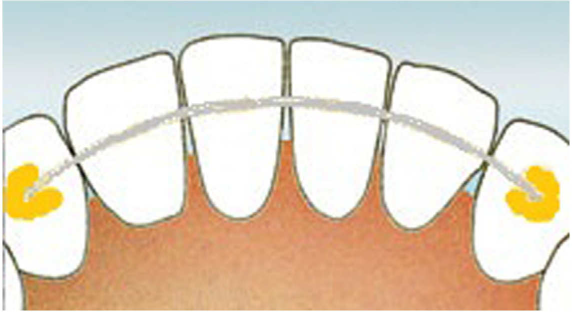
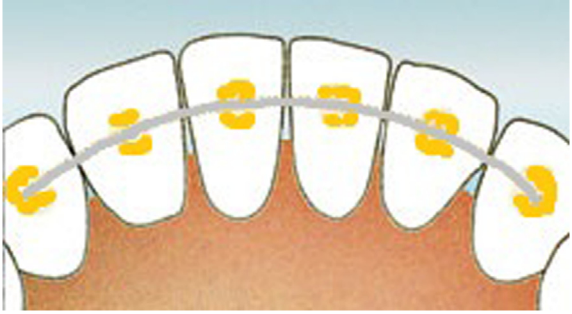


Figure 11.2 Removable retainer.



Drawing 11.1 Retainer bonded onto two canines.



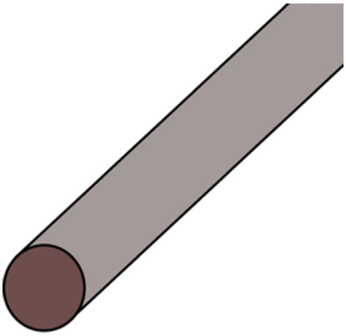
Drawing 11.2 Retainer bonded onto six lower anterior teeth.

be modified by Office), if correctly shaped and bonded to each anterior tooth, are surely effective in maintaining the teeth position. However they can undergo micro cracks or fracture at the enamel-bonding or composite-wire interface. These alterations, if not immediately detected and repaired, can lead to retainer failure (Salehi et al., 2013).

Splints and retainers may be constructed of many materials. They may be as simple as a bonded composite resin button from one tooth to another. This stabilization is transient in nature, due to the inability of composite resin to accommodate shear forces (Serio, 1999).

Retainers are now available in a huge variety of materials, type, shape, and section. Nowadays the most commonly used retainers are made with stainless steel wire, both multistrand (Drawing 11.3—PROPOSAL—to be modified by Office) or single wire (Drawing 11.4—PROPOSAL—to be modified by Office). The strands could be woven or coaxial. The number of strands usually varies between three and six, and they can have different section shapes and diameters (Meiers et al., 1998; Kumbuloglu et al., 2011).

Drawing 11.3 Multistrand wire.



Drawing 11.4 Single wire.

11.3 Longevity of the Retainers

Failure of bonded retainers may occur at the wire-composite interface, at the adhesive-enamel interface, or as a stress fracture of the wire. Although the reasons for these failures are not well studied, several factors have been reported in literature: less abrasion resistance and wear as a consequence of intermittent forces of chewing or toothbrushing, (Bearn et al., 1997); insufficient composite material (Vogel and Deasy, 1977); thickness of the wire (Foek et al., 2009); and tension between the wire and the teeth, in case of incorrect adaptation properly to enamel surface (Bearn, 1995).

Failure of a retainer may lead to unwanted tooth movement or caries development in the enamel detachment's site. In fact a disadvantage of fixed retainers is that they complicate oral hygiene procedures, and favor the accumulation of plaque and calculus. Nevertheless, the presence of a bonded retainer appears to cause no increase in incidence of caries or periodontal disease. Use of interdental cleaning aids is required to ensure adequate oral hygiene (Butler and Dowling, 2005; Labunet and Badea, 2015).

11.4 Specific Features of the FRC Retainers

Starting from the 90s, different research groups tested the feasibility and the possible use of esthetic orthodontic retainers, in order to satisfy patients' requests. Resin materials reinforced with fibers seemed to be effective, because of the promising esthetic and mechanical features (Bearn et al., 1997; Freilich et al., 1998; Vallittu, 1999; Karaman et al., 2002; Cacciafesta et al., 2008; Liu, 2010).

Fiber reinforced composite (FRC) is a material made of a polymer matrix enveloping different kinds of fibers (Eliades, 2007). These could be carbon graphite, aramid kevlar, polyethylene, boron or glass fibers. The huge variety allows the researchers to change the elastic modulus of these materials and to adjust the mechanical characteristics according to the request (Eliades, 2007). Structure and properties of FRC are described in detail in Part I of this book. Various studies showed that FRCs are less flexible than the wires commonly used for orthodontic retention and that they may occasionally fracture, but the advantages are that fiber behavior plays a very important role in determining the ability of a composite to resist to external loads by stopping, slowing, or enhancing the propagation of a possible crack (Dyer et al., 2004; Cacciafesta et al., 2007).

Polyethylene is one of the most commonly used reinforcing fibers (Fig. 11.3). More precisely it is an ultrahigh molecular weight polyethylene fiber having virtually no memory effect, i.e., due to plastic deformation of fibers it can be bended and it retains its new shape. This feature is useful to obtain an accurate and precise adaptation to the teeth surface. A polyethylene fiber reinforced composite is typically made of a woven ribbon of fibers impregnated with adhesive resin by the dentist. The feature of being braided ribbon is claimed to prevent the sliding of the fibers within the resin. Polyethylene fibers are translucent and almost colorless, allowing good esthetic/cosmetic results even in visible oral regions. Among the

Figure 11.3 Ribbond retainer.

Figure 11.4 Glass-fiber retainer.

glass fibers the most commonly used in dentistry are E-glass fibers, which chemically are alumino-borosilicate glass with less than 1% alkali oxides. There are also other types of glass fibers (A-glass, E-CR-glass, C-glass, R-glass) with slightly different chemical features (Fig. 11.4). E-glass fibers have roughly comparable mechanical properties to other fibers, such as the carbon/graphite ones. The latter are stronger and more rigid, but completely non-esthetic, being black. Furthermore, E-glass fibers are cheaper and significantly less brittle when used in composites (Meiers et al., 1998; Brauchli et al., 2009; Sobouti et al., 2016). Types of fibers used in FRCs are described in Part I of the book.

Clinical applications of FRCs are: periodontally involved teeth splinting, trauma stabilization, direct adhesive prostheses, provisional prostheses reinforcement, fixed prosthodontic appliances, resin bonded bridges, complete denture fabrication and repair, overdenture components, direct construction of posts and cores, space maintainers, active or passive tooth movement, postorthodontic retainers (Ferreira et al., 2000; Arhun and Ahman, 2008; Subramaniam et al., 2008; Bagis et al., 2010; Kumbuloglu et al., 2011; Tayab et al., 2011; Sfondrini et al., 2014a).

11.5 Chemical and Mechanical Properties of FRCs Retainers

Even differences in the polymer matrix determine different mechanical properties. Polyethylene terephthalate glycol and poly 1,4-cyclohexylene dimethylene terephthalate glycol used as polymer matrix, reinforced with continuous S-2 glass fibers, determine flexural strength and modulus of the experimental FRC of 565 MPa and 20 GPa, respectively (Goldberg and Burstone, 1992). By changing the polymer composition, the force and stiffness levels of FRCs are adjustable (Ohtonen et al., 2013). The possibility of combining different polymer matrix with different fibers according to the biomechanical needs allows the coverage of a huge variety of situations.

Nowadays the most commonly used polymer matrix is based on mono of bifunctional methacrylates. The combining of different materials and the different percentages of various components can change the mechanical properties of the product. Polymethylmethacrylate (PMMA) is a non-cross linked polymer and has a lower modulus of elasticity than a cross-linked dimethacrylate or epoxy polymers, which leads to better elastic recovery properties. Therefore adding DADD (dimer aciddiurethanedimethacrylate) monomer to the resin matrix plasticizes the polymer matrix made of cross-linked dimetharylate monomers of bis-GMA. However, only minor differences in the maximal load values and stiffness values were found based on the additional DADD monomer. The plasticizing properties of DADD monomers may be greater in creep tests, where continuous static load is applied to the FRC archwire, better simulating the clinical condition of orthodontic treatment than conventional static loading tests (Ohtonen et al., 2013).

The variety of possible usages of FRCs is due to the tailored mechanical properties. This is fundamental in order to use FRC retainers such as where metal wires have been used. Flexibility of the wire allows physiologic movement of the teeth, even when several adjacent teeth are splinted and bonded together (Jahanbin et al., 2014). When compared to metal wires FRCs retainers show better esthetic/cosmetic properties (transparency, translucency, and camouflage). Additionally, FRCs are metal-free. This last aspect is essential in the case of metal allergies, and for people who need to undergo Magnetic Resonance Imaging frequently (Sfondrini et al., 2014a). It has been demonstrated that metallic components in some body regions, even placed outside the field of view, create artifacts that affect MRI images (Wylezinska, 2015).

FRCs are frequently used as orthodontic retainers also because they can adapt easily to dental contours and can be manipulated during the bonding process. Bonding also has acceptable strength because of the integration of fibers with composite resin that leads to good clinical longevity (Goldberg and Burstone, 1992). Moreover, FRCs retainers give the possibility of connecting teeth closer to the incisal edges, which are useful from biological and biomechanical perspectives (Jahanbin, 2014).

Long-lasting mechanical properties are required from the FRC retainers. An important factor influencing the mechanical properties of FRCs is water sorption to the resin matrix itself and to micro gaps in the FRC's structure (Dyer et al., 2004; Lassila et al., 2002; Lastumäki et al., 2001). In fact, if the resin impregnation of fibers has not been complete, capillary forces can allow water to enter in non-polymerized voids inside the FRC structure and alter the mechanical characteristics (Sobouti et al., 2016). Inadequate resin impregnation with formation microgaps may take place during manual processing of fibers by dentists and dental assistants. Therefore, FRCs with resin impregnation of fibers by the manufacturer are recommended. With regard to the glass fibers and polymer matrice's stability in water, it has been demonstrated that glass FRC has good hydrolytic stability in an aqueous environment for a simulated 10-year period (Vallittu, 2007). Glass fibers represent now the gold-standard in dentistry as the silanized glass fibers allow excellent adhesion to the polymer matrix and esthetics, transparency, and camouflage (Abdulmajeed et al., 2011).

11.6 Clinical Studies About FRC Retainers

Many in vitro studies have been conducted to test FRCs retainers' flexural strength, flexural modulus and load bearing capacity. In fact, the effectiveness of a retainer should be analyzed considering different aspects: success, that can be defined as permanence of the retainer in the oral cavity with the same bonding features, without detachment, loosening, or fracture, and periodontal consequences.

A FRCs retainer at 2 years follow-up shows a success rate of 49%. The main causes of failure are retainer fracture in the upper arch and loosening in the lower arch, while the success rate of a metallic retainer appears to be 88% with detachment as a main cause of failure seen at the 2 years follow-up (Rose et al., 2002). More recent studies instead demonstrate that the detachment rate of FRC and a metal wire retainers, at a 1-year follow-up, are about 11% and 17% respectively, with no significant difference between the two groups (Scribante et al., 2011; Sfondrini et al., 2014a; Sobouti et al., 2016). The differences among various studies could be due to FRC retainers insufficient adhesion, wire deformation, trauma from occlusion, composite abrasion, technique- and operator-related factors. Also, location of the FRC retainer on the surface of the crown may influence the variation in results of clinical studies. Some authors pointed out the influence of composite coverage of the interproximal contacts, that might lead to increased calculus and compromised periodontal health. Composite coverage increases diameter of the retainer, which considerably increases the rigidity of the retainer. On the other hand, composite coverage protects the FRC-rich part of the retainer from oxygen inhibition of the free radical polymerization. Because the complete composite coverage of a FRC retainer reduces FRCs flexibility, fractures or loosenings may happen (Tacken et al., 2010).

Loosening of the retainer is related to the bonding strength between the bonding agent and enamel. Reynolds suggested that a minimum bond strength of 6−8 MPa is adequate for most clinical orthodontic needs, because these values are considered able to withstand masticatory and orthodontic forces. Commonly used adhesive systems used for FRC adhesion such as flowable composites, orthodontic composites and RMGICs has been demonstrated to show higher shear bond strength values (13.4 MPa, 23.6 MPa, and 12.5 MPa respectively of mean values) (Scribante et al., 2006). Fiber-reinforced composites allow a high adhesion value because of their chemical characteristics: Resin matrix of the FRC is chemically reacted with the methacrylate based adhesives (Cacciafesta et al, 2008; Sobouti et al., 2016).

One of the solutions proposed is to use resin modified glass ionomer cement (RMGIC) in bonding the retainer. RMGIC releases fluoride components and thus should prevent secondary caries. However, the main problems related to RMGICs are low bond strength, short working time, and hydrophilic characteristics. Regardless of the bonding materials, thus far, no differences in retainers bonding has been reported between full-bonded or spot-bonded retainers. Spot-bonded FRC retainers are claimed to reduce patients' discomfort and plaque accumulation (Heravi et al., 2015).

Some authors proposed the use of additional extraoral postcuring of FRC with light-curing oven to reduce the effect of polymerization shrinkage and to increase hardness, wear resistance and flexural strength compared to those obtained with intraoral light-curing. No significant differences in flexural strength between hand curing and additional postcuring have been reported at two different deflection parameters (1 and 2 mm) (Cacciafesta et al., 2007). Therefore clinicians can polymerize the conventional FRCs retainer direct in the patients' mouth with no need for additional postcuring, even if newly introduced nanofilled FRCs have been reported to exhibit higher flexural strength values after postcuring polymerization (Scribante et al., 2015).

During recent years many in vitro and in vivo studies have been conducted to test FRCs used for postorthodontic retention. In fact different applications have been described (Karaman et al., 2002). The main employment is fixed orthodontic retention appliance. In this case the FRCs are used as fixed retainers in an alternative to conventional metallic splints. The main advantages over conventional multistranded metal wires are excellent esthetic properties and no need for removal when patients have to undergo MRI exams. Moreover the retainer can thus be placed close to the incisal edge (Fig. 11.5). This is an advantage from both biological and biomechanical points of view (Brauchli et al., 2009). On the other hand a more difficult oral hygiene maintenance and complex repair when debonded have been reported (Andren et al., 1998). In vitro and in vivo bond strength characteristics have been studied showing conflicting results (Foek et al., 2009; Labunet and Badea, 2015).

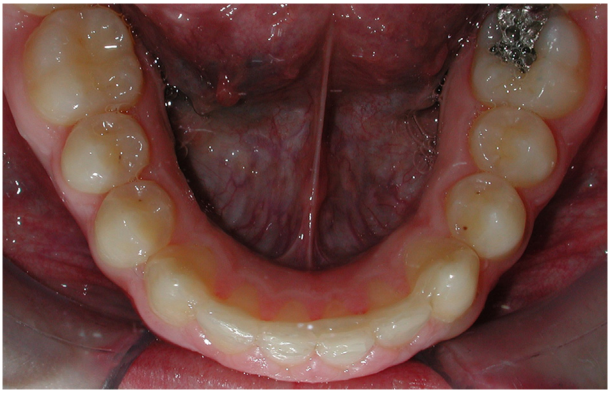


Figure 11.5 Fiber retainer close to incisal edge.

11.7 Clinical Instructions for Using FRC Retainers

FRC clinical application is slightly similar to conventional metallic retainers. Polyethylene fibers need to be resin impregnated manually but there are also preimpregnated glass fibers products on the market. First of all the correct length of FRC have to be chosen and the FRC have to be cut (with special scissors supplied by the manufacturer of polyethylene fibers to prevent unraveling) and then impregnated with a few drops of adhesive resin. The impregnated FRC has to be protected from light exposure in order to avoid early polymerization. Subsequently, after 30-seconds etchant application, washing and drying, bonding is applied onto tooth surface. FRC has to be applied to enamel surfaces with a composite. The retainer is placed closed to the incisal edge of the tooth to lower risk of loosening of the retainer. The fiber has to be fully covered with composite and then can undergo polymerization. FRC materials should always be entirely covered with composite (Brauchli et al., 2009). Manufacturers often suggest using flowable composites to cover FRCs. In fact it has been demonstrated that orthodontic composite, even if slightly less easy to use, ensures higher shear bond strength values than flowable composite and resin-modified glass ionomer cement (Scribante et al., 2006).

Another retention application of FRCs is the realization of temporary postorthodontic fixation devices or space maintainers (Tunc et al., 2012). When a space maintainer is needed, for example, between first permanent molars and first deciduous molars after second deciduous molars early extraction due to caries or fractures, an FRC space maintainer can be prepared. These devices can be easily used in order to avoid conventional metallic space maintainers with band and stainless steel extensions. The main advantages of FRCs space maintainers are that these devices can be prepared and bonded in a single appointment without the need for a dental technician (Karaman et al., 2002). Moreover, post-traumatic retention use of FRCs has been reported. In fact, when teeth (frequently incisors) undergo traumatic luxation, they can be fixed via FRCs to adjacent elements (Karaman et al., 2002).

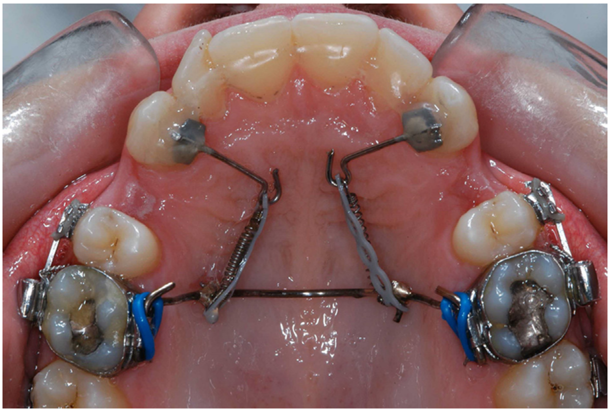


Figure 11.6 FRC used to increase anterior anchorage during a combined vestibular and lingual biomechanics.

Other authors reported use of FRCs splints to stabilize groups of teeth to increase anchorage (Fig. 11.6). For example, the use of FRCs splint as esthetic vestibular anchorage for lingual orthodontic therapy biomechanics has been reported (Cacciafesta et al., 2005). FRC retainers can be also used to speed up orthodontic treatment increasing anchorage and reducing the number of brackets placed in order to correct scissor bite or to realize other slight orthodontic movements (Cacciafesta and Sfondrini, 2006). Moreover FRC splints can be used in combination with stainless steel transpalatal bars and a power arms to increase anchorage during complex orthodontic movements (Cacciafesta et al., 2005) or to fix short pontics to rapid palatal expanders or other orthodontic appliances (Lucchese et al., 2005).

11.8 Advantages and Disadvantages of FRC Retainers

The various advantages of FRCs include ease of adaptation to dental contours and ease of manipulation during the bonding process. Because it is a relatively easy and fast technique (no laboratory work is need), procedures can often be completed in a single appointment.

On the other hand, reinforcement fibers have some disadvantages in common with rigid splints, which limit physiological tooth movement and contribute to a higher clinical failure rate (Bearn et al., 1995). However, for both techniques increased plaque accumulation has been reported. In fact it must be stated that patients who use a floss-threading device and are aware of how to floss between the teeth when wearing a fixed retainer benefit from a good oral hygiene (Rose et al., 2002). Therefore the importance of daily interproximal cleaning with dental floss is crucial (Oshagh et al., 2014). If a professional plaque and calculus removal accompanied with oral hygiene instruction is repeated every 6 months, it is likely that the periodontal health should not be compromised by the presence of bonded lingual structures (Heier et al., 1997).

Both conventional metal wire retainers and FRC retainers have their own specific disadvantages. Conventional retainers are made of active orthodontic wires and are thus rather technique-sensitive and time-consuming to position passively on the lingual surface (Sobouti et al., 2016). Additionally, these types of retainers can either debond or exert undesirable orthodontic forces on aligned teeth. Conversely, FRC retainers are expensive and also technique-sensitive to use. They may have higher failure rates, they are more difficult to repair, and they may provoke periodontal diseases when placed so close to marginal gingiva that the keeping of good oral hygiene is limited (Bearn et al., 1995; Radlanski et al., 2004; Tacken et al., 2010; Salehi et al., 2013; Sfondrini et al., 2014a).

In the literature many authors have evaluated both multistranded metal wires and FRC retainers used for postorthodontic retention with survival analysis plots (Becker and Goultschin, 1984; Dahl et al., 1991; Artun et al., 1997; Andren et al., 1998; Stormann and Ehmer, 2002; Chong and Chai, 2003; Scribante et al., 2011; Tayab et al., 2011). These studies have shown that both techniques evaluated showed high clinical success, acceptable failure rates, and good clinical reliability. Of course further studies with different fibers and further comparisons at 5 or 10 years of follow up are needed in order to assess qualities and lacks over a longer time.

11.9 Future Trends

Future research about FRCs for splinting purposes will probably be mostly focused in improving mechanical properties. The goal would be to avoid both excessive flexibility (in order to prevent the decrease of retention capacity), and excessive rigidity (to spare the risk of teeth ankylosis). Also, biologic researches are needed to test efficacy of different resin coverage and biocompatibility effects if fiber is exposed out of composite bulk. Finally, other future studies will probably analyze adhesion performances and characteristics of the increasing number of materials that are available on the market. Nanotechnology, also known as molecular nanotechnology or molecular engineering, has been introduced in the dental field. Nanotechnology is the production of functional structures in the range of 0.1–100 nm by various physical or chemical methods (Gogna et al., 2011). Dental nanocomposites provided a cosmetically acceptable result with excellent mechanical properties (Mitra et al., 2003). The main point involved with this new trend is the addition of nanofillers particles to resin-based dental materials (Paschoal et al., 2011). Recently, a nanofilled FRCs has been experimentally introduced. This new material intends to bring adequate mechanical properties. It has been demonstrated that nanofiller introduction significantly raised load values of 0.6 mm diameter FRCs. The possibility of obtaining higher load values with smaller sizes could allow clinicians to reduce retainer dimensions, thus reducing the risk of overbulking the structure and allowing the patients to be facilitated in their oral hygiene procedures (Sfondrini et al., 2014b).

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Longevity of fiber-reinforced resin composite (FRC) fixed dental prosthesis (FDP) and fabrication of direct FRC FDPs

12

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Chapter Outline

12.1 Introduction

Adhesion of resin-based materials to enamel and dentin, and developments in resin composites transformed the application of invasive therapy options to minimal invasive ones in reconstructive dentistry. Missing anterior or posterior teeth could be restored with a wide range of therapy options such as partial removable dentures, resin-bonded fixed dental prosthesis (RBFDP) made of metal-ceramic, all ceramic, indirect or direct resin-bonded fiber reinforced composites (FRC), conventional full coverage FDPs, or implants. Each of these techniques has both advantages and disadvantages, and some of the latter may include overall complexity, with biological and financial costs, and cause difficulties in maintaining oral hygiene. Full coverage FDPs present the longest track but this indication requires abutment tooth preparation yielding to irreversible biological costs. On the other hand, indication of implant-supported FDPs certainly increased dramatically over the last two decades but the incidence of biological complications such as peri-implantitis and its therapy has not been resolved yet (Faggion et al., 2010). Among the minimal invasive options, studies on metal-ceramic resin-bonded FDPs reported debonding at the metal-composite

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cement or enamel-composite cement interface (Creugers et al., 1989). Fractures and debondings were more commonly reported with all ceramic resin-bonded FDPs as the main technical complications (Kern and Sasse, 2011). In addition, favorable occlusion accompanied with sufficient space for the metal and ceramic FDPs are required in order to minimize the direct stress on the FDP (Creugers et al., 1989).

Nevertheless, RBFDPs made of metallic or ceramic materials remain costly in dentistry as opposed to polymeric ones, partly because of the material costs and in part the dental technician's cost involved. In that respect, indirect and direct FRC RBFDPs provide more economic therapy options for the patients. For clinical decision making and providing informed consent to the patients, it is beneficial to discuss the longevity of indirect and direct FRC RBFDPs and know the underlying reasons for failures for further improvement.

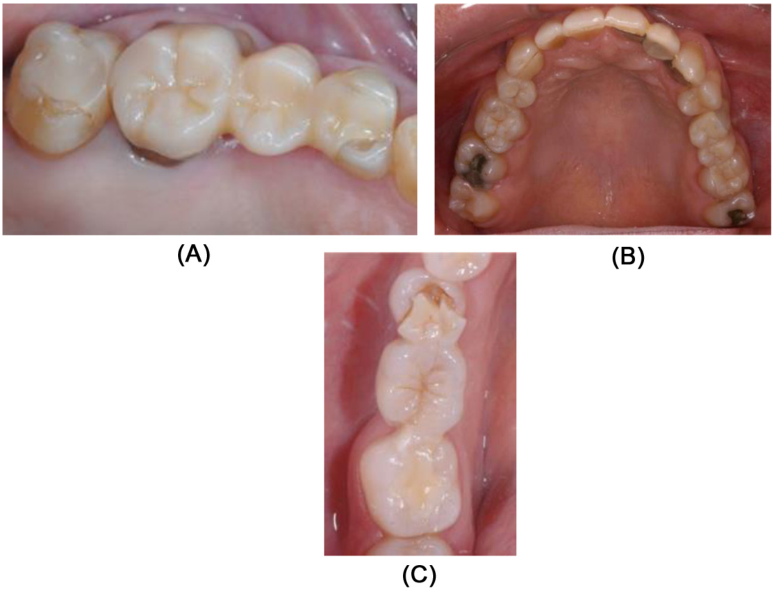
12.2 Longevity of Indirect FRC RBFDPs

Structurally, an FRC is composed of two components, namely, the resin matrix that serves as carrier and protector of the fibers, and the specifically oriented fibers with the purpose of improving the mechanical properties of resin composite. In addition to the fiber material per se, other confounding factors play a significant role on the longevity of such restorations such as the veneering material, polymerization devices, retainer type, resin cement and cementation mode.

Unfortunately, studies on clinical performance of FRC RBFDPs are limited. One systematic review on clinical survival of commercially available different FRC products without discrimination between type of retainers, fabrication technique, type of fibers, cements, preparation designs, have been published (Van Heumen et al., 2009). This systematic review reported substantial heterogeneity between studies to make estimates for survival rates at 2 years of follow-up as it was not possible to build a reliable regression model to indicate risk factors. Yet, the Kaplan-Meier estimate of the overall survival, based on the data from 435 patients in 15 studies, was 73.4% at 4.5 years (Fig. 12.1A–C).

When clinical studies are evaluated in this systematic review with a focus on longevity, it could be noticed that ultrahigh molecular weight polyethylene, E-glass or S-glass, aramid (Kevlar) and carbon fibers are the most frequently used FRC materials for the construction of RBFDPs, and for meta-analysis different fibers are all clustered as any fiber material in general (Vallittu, 1999). Among different fiber materials, silanized and preimpregnated glass fibers are certainly more commonly used because of their favorable optical properties in dentistry, and their possibility to withstand tensile stresses and prevent crack propagation in resin matrix (Dyer et al., 2005a). However, limited number of studies involved in this systematic review did not compare different FRC materials and their effect on clinical longevity.

In all the studies involved, two retainers were used. Lately, more favorable results have been reported with cantilever design (Anderson, 2005). One recent study after the systematic review focused on the resin cement type where FRC RBDPs were



Figures 12.1 (A) An indirect FRC RBFDP made of E-glass fibers on maxillary premolar to molar after 18 years of clinical function, (B) Note the debonding of the FRC RBFDP from lingual surface of the canine after 1 year of function, (C) Note the debonding accompanied with fracture of the inlay-retained FRC RBFDP between premolar and molar after 3 years of function.

bonded on two retainers in order to benefit from adhesion to enamel. Annual failure rate of 1.73% with functional survival rates ranging between 93.5 and 100% after a mean observation duration of 58 months were slightly higher than those reported in the systematic review on FRC FDPs (Kumbuloglu and Özcan, 2015).

When single studies were evaluated, similar failure types were observed in a multicenter study at 5 years with success rate of 71.2% and survival rate of 77.5% where the restoration types showed heterogeneity of inlay, hybrid, and surface-retained posterior FPDs (Van Heumen et al., 2009). As for anterior surface-retained FRC FDPs, again in a multicenter study where more operators were involved, at 5 years, survival rate of 64% and success rate of 45% was reported with median survival time of 58 months (Van Heumen et al., 2009). For surface-retained FDPs, additional mechanical retention did not improve survival significantly.

Due to the heterogeneity of the study on posterior FRC FDPs, at this moment it cannot be stated that anterior ones show less survival rate. Limited information is available on the long-term survival of all-ceramic resin-bonded FDPs but 10-year survival of such anterior FDPs made of In-Ceram with two retainers ($n = 38$; mean observation: 120 months) showed 73.9%, whereas those with one retainer ($n = 22$; mean observation: 111 months) 94.4% survival (Kern and Sasse, 2011). Such long-term evaluation with FRC FDPs is currently not available but one retainer design warrants further clinical investigation.

12.2.1 Possible factors affecting longevity of indirect FRC RBFDPs

The most commonly reported failure types with indirect FRC RBFDPs are delamination of the veneering composite, fracture of the FDP, or debonding (Van Heumen et al., 2009). Problems such as wear and discoloration are inherent problems associated with the veneering resin composites and not with the FRC materials (Gresnigt et al., 2013). Numerous in vitro studies have been carried out to measure the fracture strength of FRC FDPs under mechanical loading conditions (Dyer et al., 2004, 2005b; Özcan et al., 2005b). Cohesive delamination within the veneering resin or adhesive detachment of the veneering resin from the FRC material was also found to be the most common failure mode in clinical studies supporting in vitro findings.

Apart from the operator factor that starts with correct application of adhesive procedures, correct positioning of the fiber in the bulk of the veneering composite—one possible reason for technical failures is postulated to be the polymerization method (Souza et al., 2010). Indirect FRC FDPs are typically polymerized in laboratory polymerization devices, all which affect the degree of conversion differently. The type of polymerization device may also affect the flexural strength and Vickers hardness of the veneering composites in varying degrees. Degree of conversion is highly dependent on factors like composition of the material, color and translucency, distance of the light tip to the surface, and the irradiance of the polymerization lamp. Depending on the type of the polymerization unit, combination of light, heat, vacuum, and pressure result in an improvement from 10% to 20% in the mechanical properties of these materials as opposed to the direct polymerization techniques. Such polymerization devices usually have light intensity of 1200 mW/cm^2 and some function under vacuum. Some of these devices have one or two stroboscopic xenon lamps, and some have a mirrored circular chamber. The higher number of lamps may increase the degree of conversion. Increasing the exposure duration of the resin, which ranges from 4 minutes to 15 minutes to the light source, could improve the results. However, the increase in degree of conversion of the veneering resin covering the FRC RBFDPs could decrease the adhesion of resin luting cement on to this substrate. Prepolymerized resin composites could benefit from preliminary surface conditioning methods such as silica coating and silanization (Özcan et al., 2005b). However, in the clinical studies on FRC RBFDPs details of polymerization protocol or surface conditioning method were either not performed or not described in detail (Van Heumen et al., 2009). Thus, debonding type of failures could be in part attributed to less adhesion between prepolymerized veneer resin and the luting cement. Furthermore, the chemical composition of the veneering resin also affects the amount of remaining free monomers after polymerization. In FTIR evaluations, it was found that the UEDMA/TEGDMA phase had a DC of 70% while the bis-GMA/TEGDMA had a DC of 55% (Peutzfeldt and Asmussen, 2000). Monomer mixtures of bis-GMA and TEGDMA give rise to polymers in which the quantity of remaining double bonds increases with the content of bis-GMA, without the mechanical properties being significantly affected. This aspect should also be considered for debonding types of failures. In this context, chemical adhesion of the chosen resin cement to the prepolymerized and preconditioned resin cement is also a crucial aspect in that less adhesion could lead to initial debonding of the resin cement yielding, and to the complete detachment of the RBFDP (Kumbuloglu and Özcan, 2015). Indirect FRC RBFDPs need to be completed at least in two sessions, meaning that a temporization session is needed after making the impression. Temporary cements could not be completely removed from the dentin tubuli, making also adhesion protocols less effective (Özcan and Lamperti, 2015). Debonding type failures could be as a result of dentin contamination.

While cohesive strength of the veneering resin is partially responsible for chipping type failures, unsupported areas of the veneering resin with one of two bundles of FRCs could also be the underlying reason for veneer fractures mentioned in the clinical studies (Dyer et al., 2005b).

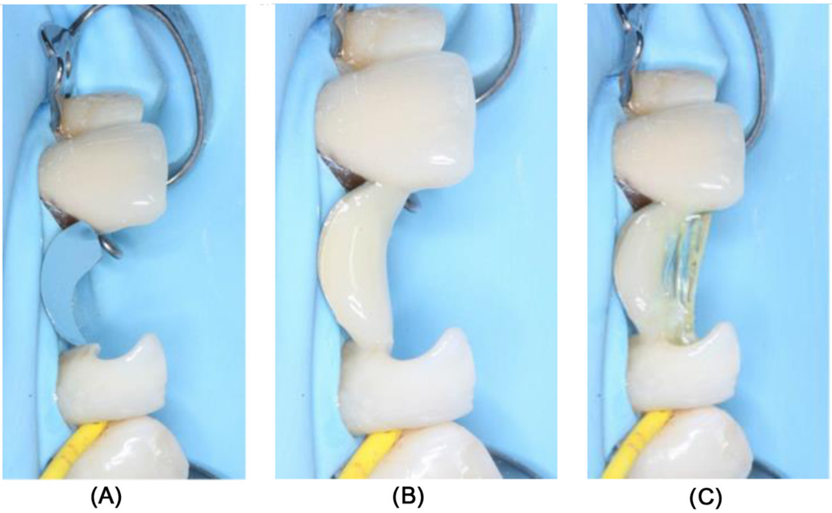
12.3 Longevity of Direct FRC RBFDPs

In direct FRC RBFDPs, impression making, laboratory procedures, temporarization, and the associated problems, are not required, also making completion of such reconstructions in one session possible. Since laboratory procedures are not required, direct FRC RBFDPs offer also economic solutions. One clinical data, on the semi-IPN resin matrix FRC RBFPDs made directly in patients' mouths, suggest high survival percentages with >96% at 5 years (Özcan, 2008). Similarly, when the corresponding surface conditioning methods are practiced, survival of direct inlay-retained FRC RBFPD on existing resin composite, amalgam, or metal ceramic on the abutment teeth, using E-glass fiber in conjunction with a posterior resin composite was reported to be 95.8% up to 6 years (Özcan, 2010).

12.4 Fabrication Method for Direct FRC RBFDPs

Direct fabrication of FRC RBFDPs requires skills in placing the FRC material, modeling the veneering resin and finishing and polishing in the mouth that is sometimes difficult in small working environment in the oral cavity. Thus, placement of rubber-dam would allow not only dry working environment but also more visibility of the ear where the RBFDP would be constructed. Placement of a resin matrix on the gingival aspect would also ensure highly polished pontic surface similar to the indirect fabrication (Fig. 12.2A–C). Furthermore, in case of existing restorations in the abutment teeth, technical surface conditioning would increase adhesion of resin composite.

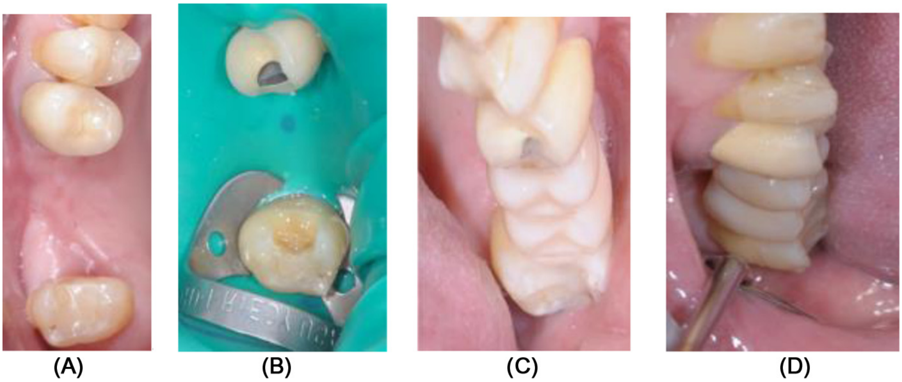
Preparation of box type of cavities with cylindrical diamond burs with dimensions of 3 × 3 mm would ensure sufficient space for flowable resin, the FRC itself, and the veneering resin. At this stage, ultrasonic burs with standard dimensions could be used. In case of abutments with metal-ceramic FDPs, the metal surface in the box should be air-borne particle abraded with alumina particles coated with silica



Figures 12.2 (A) Placement of a metal matrix would ensure polished surface of the pontic in a direct FRC RBFDP, (B) Note that the first layer of resin composite is polymerized on the metal matrix and attached on the previously conditioned surfaces of the abutment teeth, (C) Note that the E-glass fiber bundle is placed on the resin composite at the tensile side.

using an intraoral air-abrasion device at a pressure of 2.5 bar from a distance of approximately 10 mm for 5 seconds. Then, the ceramic part should be etched with hydrofluoric acid for 90 seconds, rinsed and dried. Following this treatment, one coat of silane coupling agent should be applied on the metal and ceramic surface and left to evaporate for 5 minutes. In case of intact abutment teeth, enamel and dentin should be etched with 37% H_3PO_4 for 15 seconds. After rinsing for 10 seconds and air-drying gently, the dentin surface should be conditioned with primer for 20 seconds and air-dried. Afterwards, adhesive resin should be applied on enamel, dentin, or restorative material surfaces on the abutment and it should be photo-polymerized for 20 seconds on each surface. Light intensity of the polymerization device should be initially measured by a radiometer and be ensured to be more than 450 mW/cm^2.

In order to construct the pontics, first one layer of resin composite should be placed on the metal matrix, on the rubber-dam, attached to the axial walls of the abutment teeth, and photo-polymerized for 40 seconds. After measuring the distance between the box preparations using a caliper, or orthodontic elastics, one bundle of longitudinal E-glass FRC should be cut to the same length measured. Application of flowable resin composite injected into the box preparations would increase wettability and better adaptation of the FRC bundle in the cavities. After the first fiber bundle has been carefully positioned in the bed of the flowable composite in the boxes and photo-polymerized for 40 seconds, a second bundle could be placed in situations where the bulk of the pontic is expected to be higher than 6 mm. Then adhesive resin should be applied to the entire surface of the fiber, and photo-polymerized for 10 seconds. After fillings are finished in the cavities, pontics should be built up



Figures 12.3 (A) Baseline situation with two missing in the maxilla between second premolar (metal-ceramic crown) and second molar (mesial composite filling), (B) cavity preparation on the premolar and molar to create space for the FRC material and resin composite, (C) direct FRC inlay-retained RBFDP from occlusal, (D) from buccal view after 3 years of function.

incrementally using resin composite and each layer should be photo-polymerized for 40 seconds. Following rubber-dam removal, occlusion should be checked with an articulation paper and the premature contacts should be eliminated, and finishing and polishing procedures should be performed using the polishing brushes.

After practicing interdental brush use and providing hygiene instructions, patients should be followed for maintenance protocols (Fig. 12.3A–D).

12.5 Concluding Remarks and Future Trends

Based on the present knowledge and experience, with correct design, material selection, and precise application of adhesive techniques, FRC RBFDPs could provide minimal invasive, practical, economic tooth-colored and metal-free reconstruction options with mid-term success in terms of longevity. Such reconstructions postpone other invasive and costly treatments, with expected survival times of at least 5–6 years, and with high patient satisfaction. The failures experienced in general are due to debonding of the restoration or delamination of the veneering composite. At this moment no randomized clinical study exists where this treatment approach is compared with those of implants, conventional full-coverage FDPs or RBFDPs made of metal-ceramic or all-ceramics.

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Maintenance care and repair of dental restorations using fiber-reinforced resin composites

13

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Chapter Outline

13.1 Introduction

Complete replacement of failed restorations in dentistry is usually costly and time-consuming. Defective dental restorations could always be replaced but since the introduction of adhesive technologies, repair is considered as a viable treatment option. In dentistry, repair can be described as replacing the failed or broken part of a restoration with a new one, while leaving the intact part of the restoration in place (Gordan et al., 2011). When a restoration fails as a result of small or large fractures, depending on the size of the failure, instead of replacement, restorations could be repaired. This can be achieved by adding a new layer of resin composite onto an existing restoration material. Since every replacement would lead to a larger preparation size, repairs could slow down the so-called restoration cycle (Blum et al., 2003; Elderton, 1990).

Intraoral repair of failed direct or indirect restorations is typically accomplished using resin-based composite materials. For adhesion of composites to substrates other than tooth substance, a number of surface conditioning methods have been

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developed based on physical, physico-chemical or chemical adhesion principles (Özcan et al., 1998). While in the physical conditioning methods surface roughening is achieved using air-borne particle abrasion, lasers, etching agents such as acidulated phosphate fluoride, hydrofluoric acid, and phosphoric acid, chemical conditioning methods involve the use of silane coupling agents and/or intermediate adhesive resins. Here, the composition of the substrate is the most important determining factor in the success of the repair. Furthermore, the use of FRCs contributes to the interfacial strength of repaired joints in repair of some restoration materials (Özcan et al., 2006a, 2006b).

13.2 Surface Conditioning Methods

13.2.1 *Acid etching methods*

Etching of substrates in dentistry is typically achieved using phosphoric acid (H_3PO_4) or hydrofluoric (HF) acid. Typically, 37% H_3PO_4 is effective on enamel and dentin for microretention but it has no direct effect on surface characteristics of composites, ceramics, and metals. Therefore, when a failed restoration has enamel/dentin margins, conditioning these substrates would add to the overall retention of the resin composite and prolong survival of repaired restoration (Loomans and Özcan, 2016).

The other most commonly used etching agent in dentistry to condition the dental material surfaces is HF acid. From a chemistry perspective, HF is the inorganic acid of elemental fluorine (Özcan et al., 2012). Hydrogen fluoride is produced by the reaction of calcium fluoride (CaF_2) and sulfuric acid. HF solutions can be formed when fluoride salts are acidified with acidic solutions. As it is a weak acid, hydrogen fluoride in water for instance is not completely ionized. Its conjugate base, the fluoride ion F^-, can re-associate to form HF in solutions with low pH. In strong acidic solutions, the pH of the fluoride-containing mixture will be low and the free F^- formed from the ionization of the fluoride salt in aqueous solution will exist as HF. When accidentally released, HF can diffuse as a dense vapor and aerosol. HF itself is not flammable, explosive, or oxidizing but it is a highly reactive chemical. Hence, its storage conditions and handling must be taken into account when using this acid. When using hydrofluoric acid intra-orally, direct contact with enamel and dentin as well as skin or mucosa should be avoided. To date, no side effects or negative reactions of hydrofluoric acid have been described in the dental literature (Özcan et al., 2012).

Since the introduction of glass-based ceramics and the discovery of the benefits of adhesive cementation in dentistry, HF started to be used to condition restorative and prosthetic devices. Strong bonds are formed between resin-based materials and dental ceramics that are etched with HF (Özcan and Vallittu, 2003). This is based on the affinity of fluoride to silicon that is higher than to oxygen: $4HF + SiO_2 \rightarrow SiF_4 + 2H_2O$. By the selective removal of the glassy matrix, principally micromechanical retention is achieved between the resin and the etched ceramic. The greatest advantage of the use of HF for ceramics is that its chair-side application is very simple and for this reason sophisticated conditioning methods may not be necessary.

There is much uncertainty on the optimal concentration of hydrofluoric acid and most effective etching duration. Nevertheless, prolonged etching time does not necessarily result in better adhesion. Depending on the ceramic type and the composition of the glassy matrix, prolonged etching time may remove dissolved glass particles from the surface yielding to less optimum roughness and wettability of the subsequent silane coupling agent (Leite et al., 2014). Typically, duration of etching feldspathic ceramic with 9.6% HF is 2−3 minutes; leucite reinforced ceramics with 5% HF for 1 minute, lithium disilicate reinforced ceramics: 5% HF for 20 seconds (Özcan and Volpato, 2015). Uneven wettability of HF results in decreased wettability of the resin, which could hamper effective etching. Furthermore, the etched surface should be washed and rinsed, for as long as the etching duration, under copious water. HF etched ceramic restorations should be further neutralized for at least 1 minute using neutralizing agent, which is a mixture of $CaCO_3$ and $NaHCO_3$ powder mixed with distilled water. Neutralizing solution helps to remove the hazardous HF remnants from the pores and neutralizes the pH of the ceramic surface.

Unlike phosphoric acid, HF dissolves glass particles present in ceramics and in most of the composites leaves the resin matrix unaffected. Particularly in microfilled composites less inorganic filler particles are present and therefore the effect of etching with hydrofluoric acid in this type of composites is particularly limited (Loomans and Özcan, 2016). Composites containing zirconium clusters or quartz fillers for instance will react less upon hydrofluoric acid etching than on composite resins consisting of barium-glass fillers.

13.2.2 Air-borne particle abrasion methods

Achieving a clean substrate surface by removing the uppermost contaminated layer is crucial for durable adhesion of repair resin to any material. Airborne particle abrasion is a commonly used method chairside for intraoral repairs, which removes any organic contaminants from the material surface, increasing the wettability of adhesives. Moreover, the increased bonding surface area and surface roughness allow for micromechanical interlocking of the repair composite. An increase in surface area of approximately 80% can be attained depending on the material after air-abrasion, which increases bonding sites available to react with an adhesive promoter (Özcan, 2014).

In dentistry, air-abrasion systems rely on different particle types and sizes ranging between 30 and 250 μm. While particles of 110−250 μm are typically used in dental laboratories, chairside air-abrasion for repairs is accomplished using 30−50 μm particles. Essentially, the impact of air-abrasion protocols could promote surface roughness. However, this phenomenon is highly dictated by the accompanying parameters during air-abrasion such as the particle morphology, particle size, deposition duration, nozzle distance, nozzle diameter, and most significantly by the pressure.

Airborne particle abrasion for intraoral repairs is achieved utilizing chairside air-abrasion devices operating under a pressure of between 2 and 3 bar. The substrate material, metal, ceramic, composite, or amalgam to be conditioned is then abraded approximately for 10 seconds from a distance of approximately 10 mm to achieve a clean and rough surface. Prolonged duration of air-abrasion may be needed depending on the size of the defect. The particles used consist of aluminum oxide particles (Al_2O_3) with a size of 30−50 μm or aluminum oxide particles coated with a silicium-oxide layer (SiO_2) where the latter is referred as "silicoating" or "tribochemical surface conditioning." Alumina or silica particles coat the surface that makes then covalent bonds through siloxane layer with the silane coupling agent. Since one disadvantage of air-abrasion is the aerosol with abrasive particles, a good suction device is mandatory to prevent aspiration of these particles.

13.2.3 Silane coupling agents and adhesive resins

Following air-abrasion or etching with HF, chemical adhesion can be established using special primers or monomers that react with the surface of a material. In dentistry, usually 3-methacryloxypropyltrimethoxysilane (MPS) is used which is a bifunctional molecule (Matinlinna et al., 2004). MPS silanes consist of a methacrylate group on one side, that can react with the intermediate adhesive resin and composites, and on the other side a reactive silanol group that can form siloxane bonds with the alumina and/or silica present on the air-abraded or etched substrate surfaces.

Silane coupling agents are presently available in two types, namely either hydrolyzed or non-hydrolyzed (Matinlinna et al., 2004). The hydrolyzed silanes are directly ready for use and should be applied as a separate step in the bonding procedure before the adhesive resin is applied. The non-hydrolyzed silane has to be activated first with an acid, usually an acidic monomer (i.e., 10-Methacryloyloxydecyl dihydrogen phosphate, 10-MDP), which is present in the primer or adhesive resin. Depending on the adhesive system, the silane coupling agent has to be mixed with the primer or adhesive resin. In vitro studies showed significant positive effects of the use of silane coupling agents in composite or ceramic repairs compared to those situations where no silane was used (Özcan, 2003b).

Chemical adhesion of composites to precious and non-precious metals could be achieved by applying special metal primers (Barkmeier and Latta, 2000). While acid etching is not effective on metal surface, air-abrasion followed by metal primer application increases the adhesion significantly. Some metal primers contain 10-MDP monomer that chemically bonds to the oxides present on non-precious metals and improves the wettability of the surface. Additionally, some metal primers also consist of the monomer 6-[*N*-(4-vinylbenzyl) propylamino]-1,3, 5-triazine-2,4-dithione (VBATDT) that makes a more durable chemical bond with the precious metals (Matinlinna et al., 2004). These metal primers should be applied after air-abrasion and subsequently adhesive resin is coated on the silanized/primed substrate surface.

Silane application is then followed by the application of adhesive resin that increases the wettability of the repair resin composite.

13.2.4 Application of FRC woven sheets

Although it cannot be classified as a surface conditioning method, the use of FRC materials could act as crack stoppers in laminated or layered structures and thereby increase repair strength. In general, stress concentrations within the resin and the interface can be relieved by initiation of a crack and its propagation through the resin until it meets the fibers, resulting in debonding of the resin composite. The polymer matrix between the glass fibers (semi-interpenetrating polymer network of polymethylmethacrylate and cross-linked dimethacrylates) could behave as low modulus stress breaker between the restorative material such as amalgam (Fennis et al., 2004; Özcan et al., 2006a) or metal-ceramic (Özcan et al., 2006b) and repair resin.

In an attempt to increase the interfacial strength and change the crack propagation, 0.06 mm E-glass woven fibers could be employed in repair actions. Laminated composite plates are extensively used in the construction of high performance structures, etc., in the aerospace, civil, marine, and automotive industries, due to their high stiffness and strength, excellent fatigue resistance and long durability. Due to the anisotropy of composite laminates and non-uniform distribution of stresses in the laminae under either static or dynamic loading, the failure process of laminates is very complex. Unfortunately, laminated composites have relatively poor mechanisms for absorbing energy due to local impact damage where loading is normal to the laminae planes (Wang et al., 2006). For this reason, application of fibers at the interface between two or three laminates may change the load bearing capacity of the whole structure.

It is well known that the quantity and location of the fibers in a composite construction could affect the delamination mode of fiber-reinforced composite laminates (Dyer et al., 2004). Ideally, fiber sheet should be placed at the tensile region of a reconstruction to be repaired. In laminated fiber reinforced composites, crack growth under tensile stresses is generally arrested by the fibers. Increasing the quantity of fibers could increase the interfacial strength but then the thickness of the fiber could impair the marginal adaptation, which would lead to marginal discoloration or interfere with occlusion in dental applications.

By using fibers between the laminae, resistance to fatigue crack propagation could be increased and failure then happens only at high stress levels. Under the influence of compressive cycle stresses however, the damage associated with delamination and separation of the fiber-reinforced layers, which are stacked together to form laminates, must be taken into account. The presence of delamination may reduce the overall stiffness as well as the residual strength leading to structural failure. Low delamination resistance then causes delamination cracks (Chai et al., 1991). Since the areas to be repaired in dental applications do not exceed 2−3 mm in thickness, one or two layers of thin FRC woven sheets should suffice to reinforce the substrate-composite interface (Gresnigt and Özcan, 2007).

13.3 Amalgam Failures and Repair Protocol With and Without FRC

Amalgam has served dentistry for more than a century. Although amalgam fillings undergo constant corrosion and they might not fulfill all cosmetic-esthetic demands, they are still commonly used. The results of recent surveys from cross-sectional studies indicate that complete cusp fracture of posterior teeth associated with amalgam restorations is a common problem in dental practice (Fennis et al., 2002).

A number of factors seem to contribute to the fracture of teeth with or without loss of tooth substance and amalgam material, such as occlusal instability, impact load, fatigue load during mastication, secondary caries, microdefects, technical errors, insufficient sound tooth material available surrounding the restoration (undermining cusps) or occlusal prematurity. In addition, the more surfaces restored and/or the wider the isthmus, the greater the chance of cusp fracture (Fennis et al., 2002). Thus it is likely that the restorative status of the tooth has an influence on the incidence of fracture. The majority of the fractures were observed in the supragingival location, which suggested that the fractured tooth could be restored easily. Although there is little published literature on the subject, repair of a restoration is more cost-effective than total replacement wherever appropriate. Intraoral repairs using resin composite for teeth restored with amalgam that suffered fractures with or without cuspal involvement, could extend their survival time in a minimal invasive and economic fashion.

For durable repairs, exposed amalgam surface with and without cusp fracture need to be conditioned using surface conditioning methods, adhesion promoters, and composite materials accordingly. Since both amalgam and tooth substrate (enamel and/or dentin) require different surface conditioning protocol, cross contamination of each method may impair adhesion and thereby, durability of amalgam repairs. Thus, the following surface conditioning and bonding protocol could be recommended based on the available scientific reports (Özcan and Volpato, 2015).

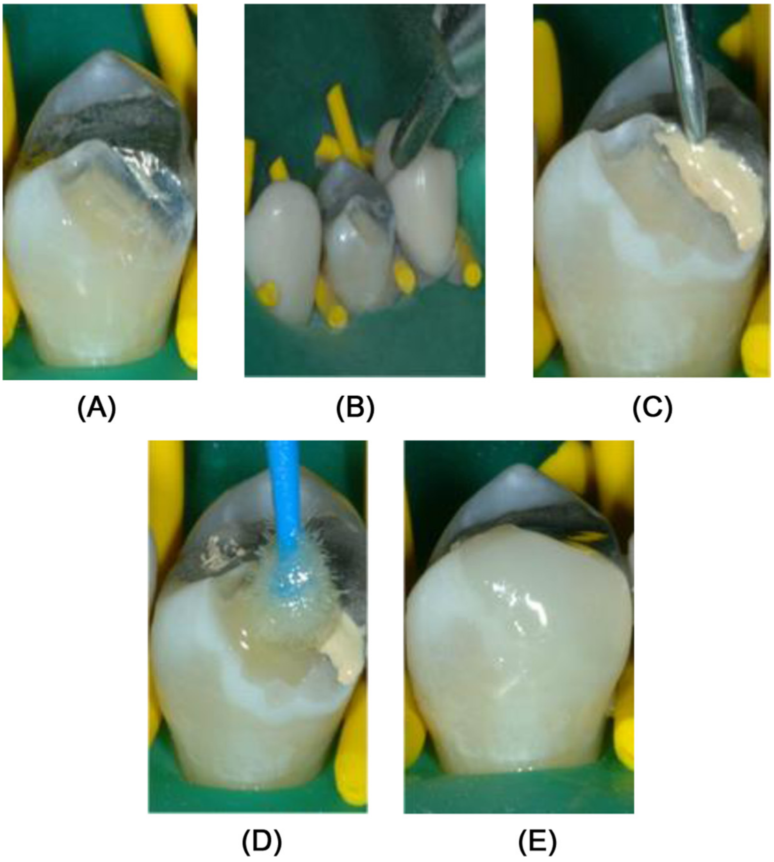
Before performing the intraoral repair, it should be ensured that there are no premature contacts. The fractured area and the presence of cusp fracture with or without dentin exposure should be carefully evaluated and the location of the fracture line should be noted. Fractures located subgingival requires absolute isolation, and the presence of dentin next to amalgam requires dentin conditioning for intraoral repair using resin composite.

The area to be restored should be isolated with a rubber-dam and the fracture surface should be cleaned using fluoride-free prophylaxis paste or pumice. Initial mechanical cleaning eliminates pellicle or other contaminants from the substrate surface for better adhesion of the resin composite. Then bevel should be created in enamel using a fine-grit diamond bur. Bevelling enamel exposes more enamel prisms and a more favorable etch pattern for micromechanical retentions, providing improved marginal quality, retention, and a smooth transition between the tooth and the resin composite. The exposed amalgam surface should be air-abraded, preferably with alumina particles coated with silica (i.e., 30 μm, CoJet, 3M ESPE, USA) using an intraoral air-abrasion device at a pressure of 2.5 bar, from a distance of approximately 10 mm for 5 seconds. The chairside tribochemical silica coating method modifies the metal surface and provides micro-roughness that is essential for mechanical bonding. However, surface roughening alone does not dictate the bond strength of resin composite to amalgam.

After air-abrasion is accomplished on the amalgam surface, enamel and dentin should be etched with 35% H_3PO_4 for 15 seconds, rinsed and dried with oil free air. Amalgam is an alloy where mercury plays an essential role, but the exact mechanism of adhesion to amalgam is unclear. Silane coupling agent and MDP-VBATDT containing primer alone did not provide durable covalent bonds with amalgam (Watts et al., 1992). Since the repair of amalgam restorations with amalgam is not reliable with mechanical interlocking only (Mjör, 1993), an adhesive approach should be considered. After silane coupling agent is applied on the amalgam surface and we wait for its reaction for 1 minute, dentin should be primed for 15 seconds and gently dried. The reflection of the amalgam under the repair composite may result in poor aesthetic appearance. Masking the amalgam surface with opaque resin prevents metal shine through. Therefore, with the tip of a probe, a thin layer of powder-liquid type of opaque resin should be applied on the silanized amalgam surface. Powder-liquid type of opaque resins wet the metal surface better than paste ones (Özcan and Kumbuloglu, 2009). It has to be ensured that opaque layer is free of air-bubbles. Photo-polymerization of the opaque resin for 120 seconds with a polymerization device with light intensity of at least 400 mW/cm^2 increases adhesion of opaque resins to metals (Özcan and Kumbuloglu, 2009). Prolonged duration of photo-polymerization is needed for such opaque resins since they contain pigments in their composition some of which retard polymerization.

Following opaque resin application, adhesive resin should be applied with a clean microbrush, on enamel and dentin surface, gently air-thinned and photo-polymerized for 20 seconds. Application of adhesive resin on amalgam may dissolve some opaquers; smear this layer on the enamel/dentin compromising aesthetics. Here, adhesive resin should either not be applied or not scrubbed on amalgam. Finally, repair composite is applied incrementally on the fractured area and photo-polymerized for 40 seconds. After removing the rubber-dam, premature contacts in occlusion should be eliminated with a fine bur and finishing and polishing should be performed on the repaired area with rubber tips, brushes, and polishing pastes.

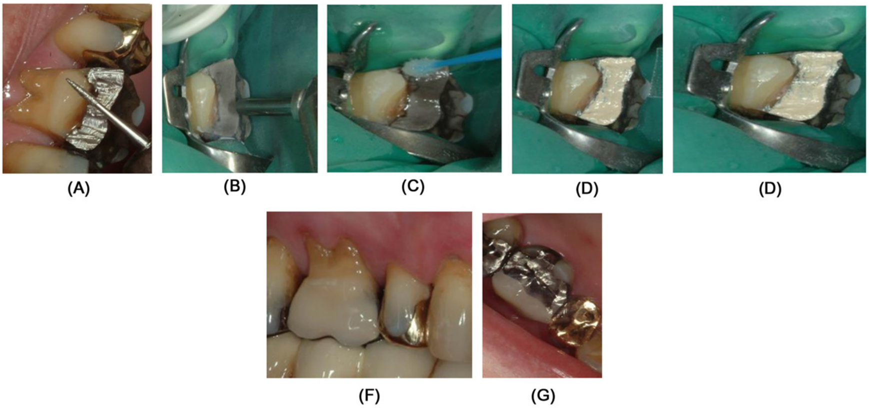
Repair of amalgam restorations with resin composite is a conservative treatment approach. However, if the quality of amalgam filling is not acceptable or caries is present, repair action should not be contemplated and the restoration should be replaced. In large amalgam repairs, application of a pre-impregnated continuous bidirectional E-glass fiber sheet (thickness: 0.06 mm) on the opaque layer may increase repair strength (Özcan et al., 2006b) (Figs. 13.1 and 13.2).



Figures 13.1 (A) Amalgam exposure associated with cusp fracture on a premolar, (B) intraoral air abrasion of amalgam, (C) after silanization, opaque resin application with the tip of a probe, (D) adhesive resin application, (E) repair of the cusp with resin composite.

13.4 Metal Ceramic Fixed Dental Prosthesis Failures and Repair Protocol

Despite the increased effort to improve the bond between ceramic materials and metal substrate, fractures of ceramic-fused-to-metal FDPs still occur. The reasons for failures cover a wide spectrum from thermal mismatch between the veneering ceramic and the metal framework, lack of calibration of the ceramic oven, laboratory mistakes, to iatrogenic causes, or that they are merely related to the inherent brittleness of the ceramics (Özcan, 2003a). The reasons for such failures are usually, due to lack of slow cooling of the furnace, lack of anatomical support of the framework, inadequate framework-veneer proportion, inadequate firing procedures, lack of compatibility in thermal expansion coefficients of framework. While early fractures are due to technical problems, the late fractures are frequently due to



Figures 13.2 (A) Large amalgam exposure associated with cusp fracture on a maxillary molar, (B) intra-oral air abrasion of amalgam, (C) silane coupling agent application, (D) opaque resin application and the addition of E-glass woven fiber (0.6 mm) for interfacial reinforcement, (E) adhesive resin application, (F) repair of the cusp with resin composite (buccal view), (G) repair of the cusp and refurbishment of the old amalgam in an attempt to prolong service life of a defect restoration (occlusal view).

repeated stresses and strains during chewing or trauma (Özcan, 2003a). Repairing FDPs in vivo can increase the clinical longevity of the failed restorations, thereby offering the patient and the dentist a cost-effective alternative to replacement. However, the repair of fractured metal-ceramic FDPs represents a potential clinical challenge, particularly when the metal substructure has been exposed, and when bonding of resin to metal alloy is required (Özcan and Niedermeier, 2002) (Fig. 13.3).

The use of E-glass fiber weaves impregnated with polymer-monomer gel resin in case of large metal exposure was shown to increase repair strength and cause exclusively cohesive failure between in the FRC itself (Özcan et al., 2006b) (Fig. 13.4). This indicates that FRC provides a strong bond of the veneering repair resin on the metal/ceramic surface. Polymethylmethacrylate enrichment on the fiber weave surface needs to be treated with a resin having a dissolving parameter of PMMA, or extensive resin treatment times are needed which may be in some cases not possible for direct repairs. The higher results obtained with the use of FRC weaves in metal-ceramic repairs imply the following: the stress concentrations in the repaired crowns cause initiation of a crack, and it propagates through the resin until it meets the FRC layer with continuous fibers that stop the crack or deviate the direction (Özcan et al., 2006b).

Repair actions could be performed multiple times. One could expect that after each repair cycle, the repair surface area changes. Nevertheless, air-abrasion of the metal surface, HF etching the ceramic margins, and application of 0.6 mm E-glass woven fiber increases the adhesion of the repair composite to metal-ceramic (Özcan et al., 2006b).

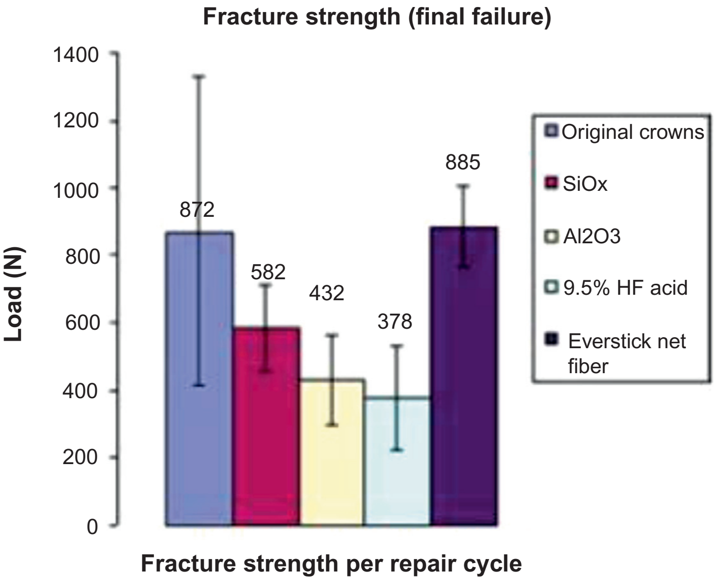
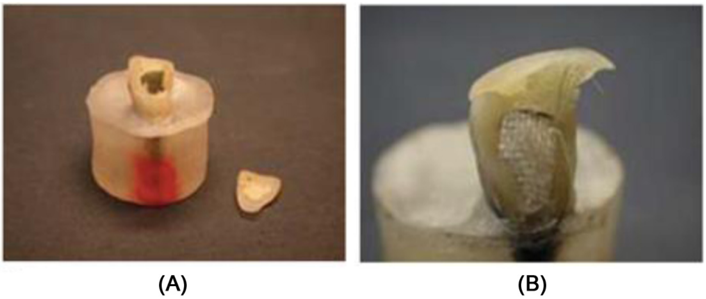


Figure 13.3 Mean fracture strength (N) of repaired metal-ceramic crowns using different surface condition methods. Note that the use of E-glass woven fibers at the metal-repair resin interface restored the fracture strength to the original fracture strength of the metal-ceramic crown.



Figures 13.4 (A) Adhesive failure type with metal exposure when metal surface was only air-abraded, silanized and with opaque resin coated, (B) Cohesive failure type in the fiber when two layers of E-glass woven fibers of 0.6 mm were used to increase the interfacial strength.

Both metal and ceramic substrates require different conditioning methods with etching gels, adhesive promoters, and/or abrasives. Thus, the sequence of repair protocol may affect durable adhesion of repair composite to these substrates.

Chippings or fractures of veneering ceramic are multifactorial, one of which is the presence of premature contacts. This could be the underlying cause for failure and should be eliminated prior to repair procedures. The color match between ceramic and resin composites, especially in the visible anterior areas, is crucial as the two materials have different surface properties and color stability. Rubber-dam will protect the soft tissues from hazardous hydrofluoric acid (HF) that will be used later for conditioning the veneering ceramic. Ceramic and metal surface should be cleaned using fluoride-free paste or pumice. Glaze of the veneering ceramic surface at the margins to be repaired should be removed using fine grit diamond bur under water-cooling and bevel should be created. Undisturbed glaze layer with concentrated glass particles will not react with HF and subsequent application of silane coupling agents. Removal of the glaze layer would also increase the surface area on ceramic for mechanical retention and allow for the reaction of silane with the glassy matrix. Accidental deposition of particles during conditioning the exposed metal by air-abrasion may remove the glaze on the veneering ceramic. Thus, the veneering ceramic, except the bevelled area, should be coated using glycerin gel.

The metal surface should be air-abraded using a chairside air-abrasion device, preferably with alumina particles coated with silica or silica only (particle size range: 30–50 μm; blasting pressure: 2.5 bar), for approximately 5 seconds until the metal surface turns matte, from a distance of approximately 10 mm in circling motion, rotating the nozzle. After washing and rinsing under copious water and drying, the ceramic margins where the repair composite will be adhered to should be etched with 5% or 9.6% HF for 20 or 90 seconds depending on the ceramic type. After rinsing and neutralizing the surface, silane coupling agent should be applied on both the metal and the ceramic surface, one layer, and a 1 minute wait for its reaction. The metal surface would be then masked with opaque resin based on the powder-liquid system as described above. At this stage, in case of largely exposed metal surfaces, one or two sheets of 0.6 mm woven E-glass fiber could be applied to increase interfacial strength. Then, adhesive resin should be applied and photo-polymerized for 20 seconds. After completion of incremental repair resin application, and polymerization, premature contacts should be eliminated and finishing and polishing should be performed accordingly.

13.5 Concluding Remarks and Future Trends

Repair of failed restorations due to technical reasons or fatigue could prolong the survival of functioning restorations. However, it has to be made sure that the underlying reason for the failure does not constitute the fundamental reason for failure. If this is the case, restoration needs to be replaced. Nevertheless, in addition to the use of physical, chemical, and physicochemical conditioning methods, the use of woven E-glass fiber sheets increases interfacial strength and thereby contributes to more durable repair actions. Although interfacial strength is increased in repairs, degradation of repair resin surface may again require additional repairs during the whole course of service life of a direct or indirect restoration.

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