CURRENT PERSPECTIVES IN CLINICAL DENTISTRY

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PREFACE

Dentistry is a constantly evolving discipline shaped by scientific developments and technological innovations. *Current Perspectives in Clinical Dentistry* brings together chapters covering key areas, including biomimetic dentistry, pediatric occlusion assessment, laser applications in restorative dentistry, patient-centered outcomes in periodontal disease, subperiosteal implants for severely atrophic jaws, and implant strategies in the aesthetic zone.

Each chapter provides a concise overview of recent advances, clinical considerations, and emerging trends, emphasizing the integration of scientific evidence with clinical practice. This volume aims to serve as a practical resource for clinicians, researchers, and students seeking insight into contemporary dental practice.

I sincerely thank all contributing authors for their expertise and dedication, and the staff of UBAK Publishing for their support in bringing this work to fruition.

Sincerely,

14.03.2026

Assist. Prof. Dr. Fatma ALTIPARMAK

EDITOR

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CHAPTER 1

BIOMIMETIC DENTISTRY

DDS Cansu YIKICI ÇÖL

1. INTRODUCTION

Definition and historical background of the concept of biomimetics: The term biomimetics derives from the Greek roots bios (life) and mimesis (imitation). In dentistry, the biomimetic concept is based on the principle that, while repairing damaged dental tissues, restorations should imitate the structure, function, and durability of the tooth's natural tissues (such as enamel, dentin, and cementum) (Eldafrawy et al., 2018). This approach aims to achieve aesthetic and biomechanical outcomes comparable to those of the natural tooth while preserving its vitality and integrity. The foundations of biomimetic thinking were established in the mid-twentieth century: in 1950, Otto Schmitt introduced the term biomimetics, and in 1974 the concept was included in dictionaries for the first time(Hwang et al., 2015). In dentistry, the development of the biomimetic approach accelerated with the advent of adhesive dentistry. Indeed, in 1955, M. Buonocore predicted that, with the development of restorative materials capable of bonding to the tooth surface via the acid-etch technique, "there would no longer be a need for a retention form in cavity preparation."(Buonocore, 1955). This vision initiated an "adhesive revolution" based on the concept of chemical bonding rather than

traditional amalgam restorations and mechanical retention. In the subsequent decades, the concept of biomimetic restoration progressively matured with advances in adhesive systems and tooth-colored materials such as composites and ceramics (Alleman et al., 2017).

The necessity of the biomimetic approach in dentistry: Traditional restorative treatments were generally performed according to the principle of extension for prevention, involving extensive removal of tooth structure, including sound tissue. Particularly for amalgam restorations or full crowns, even non-carious areas were prepared, leading to unnecessary loss of dental tissue. In contrast, the biomimetic approach adopts the principle of removing as little tooth structure as possible: the motto “Less dentistry is the best dentistry” succinctly summarizes this philosophy. The objective is to preserve healthy tooth tissues to the greatest extent possible while repairing only the damaged portions. In this way, the tooth maintains its natural strength after restoration, and the risk of cracks and fractures decreases due to the avoidance of unnecessary tissue removal. Moreover, because the pulp can remain vital with a minimally invasive approach, the long-term survival of the tooth increases and the cycle of retreatment is prevented(Singer et al., 2023). Biomimetic restorations have been shown to reduce microleakage compared with conventional treatments, thereby decreasing postoperative sensitivity and the incidence of secondary caries(Alleman et al., 2017). In conclusion, the biomimetic approach in dentistry provides more durable and biocompatible

restorations while preserving the natural structure of the tooth, thereby aiming to enable patients to maintain healthy use of their teeth throughout life.

Difference between the biomimetic perspective and conventional treatments: The most prominent distinction between the biomimetic approach and classical methods lies in the level of preservation of tooth structure. In the conventional approach, the lost tissue was replaced with rigid materials harder than the tooth, often requiring macro-mechanical retention (e.g., creating undercuts in the cavity or placing pins). In contrast, biomimetic restorations employ advanced adhesive techniques to achieve strong chemical bonding to both enamel and dentin; thus, retention of the restoration is ensured without the need for additional retention forms(Burke, 2003). For example, whereas the conventional approach to the treatment of deep caries would involve preparing even sound areas to place a large amalgam restoration or crown, the biomimetic perspective removes only the carious tissue, preserves the intact structures, and re-establishes tooth integrity with an adhesive restoration.

This difference is a fundamental factor contributing to the superior long-term success of biomimetic restorations. In conclusion, the biomimetic perspective adopts the principle of “preserve the tooth first,” in contrast to the classical approach, and paves the way for minimally invasive, tissue-conserving treatments in modern dentistry(Alyahya, 2024).

2. FUNDAMENTAL PRINCIPLES OF BIOMIMETIC DENTISTRY

2.1. Structural and Biomechanical Properties of Natural Tooth Tissues:

What renders a tooth strong and durable in its natural state is the harmonious organization of different tissues such as enamel and dentin. The enamel layer is highly mineralized and extremely hard, possessing an elastic modulus of approximately 80–90 GPa; however, this hardness also makes it brittle. Dentin, in contrast, is softer and more flexible (elastic modulus ~15–20 GPa) and exhibits shock-absorbing behavior due to its collagen network. For this reason, enamel does not exist alone in nature; it is always supported by underlying dentin. The dentino-enamel junction (DEJ), the transition zone between enamel and dentin, acts as a natural adhesive uniting these two materials and plays a critical role in load distribution. Research has demonstrated that dentin support is decisive in enabling enamel to resist masticatory forces and that enamel structure gains increased toughness particularly in the DEJ region. In other words, enamel cannot remain strong without the flexible dentin beneath it; dentin compensates for enamel's brittleness, and together they function as a layered structure. Understanding the natural biomechanics of teeth forms the basis of biomimetic restoration design. For example, in the natural tooth, the enamel–dentin relationship allows resistance to high chewing forces without crack formation. Therefore, biomimetic treatments ideally reproduce a similar combination of a rigid superficial layer (enamel-

like) and a flexible underlying layer (dentin-like). Moreover, the pulp–dentin complex is a living structure with defensive and reparative capacity; fluid movement within the pulp confers flexibility to dentin and helps prevent the propagation of small cracks. Mimicking these unique structural characteristics of natural dental tissues is critical for the success of biomimetic restorations(Zafar et al., 2020).

2.2. Simulation of Dentin-Enamel Junction (DEJ):

The DEJ, the interface between enamel and dentin, is not only a physical boundary but also a mechanical cushioning zone. The DEJ region gradually balances the elasticity difference between enamel and dentin and prevents crack propagation. One of the important principles of biomimetic approaches is to create a similar transition zone at the restoration–tooth interface. The hybrid layer obtained with modern adhesive systems functions almost like an artificial DEJ, thanks to the micro-mechanical interpenetration of resin monomers with the dentin collagen network. Studies have shown that the tensile strength of a high-quality dentin bond can reach the range of 30–60 MPa and that this is equivalent to the tensile strengths of natural enamel, dentin, and the DEJ(Alleman et al., 2017). This demonstrates that, with properly applied adhesive techniques, the restoration can bond to the tooth as strongly as the original DEJ. Another strategy in mimicking the DEJ is the use of graded-structure materials. For example, researchers have developed functionally graded ceramics that combine dentin and enamel-like properties within the same block; in these materials, high-strength regions are located in the deeper portions, while aesthetic and

translucent layers are present at the surface, with a gradual transition in between(Michailova et al., 2020). Similarly, bilayer composite restoration systems have been developed: the combination of a flexible glass-fiber-reinforced underlying composite layer and a harder, wear-resistant superficial composite layer mimics the fibrous structure of the dentin–enamel complex. In such a restoration, the underlying layer, like the DEJ and dentin, dissipates loads from the upper layer and arrests the propagation of potential microcracks(Singer et al., 2023). In conclusion, the objective of biomimetic restorations is to achieve a structural gradient capable of distributing and absorbing forces applied to the tooth in the same manner as a natural tooth. To accomplish this, adhesive interfaces, fiber or particle-filled intermediate layers, and graded material technologies are used to mimic the role of the DEJ.

2.3. Reducing microleakage and preventing cracks:

One of the most important factors threatening the long-term success of a restoration is microleakage, and another is the formation of microcracks. Microleakage occurs when bacteria and fluids infiltrate microscopic gaps that may form between the restoration and the tooth, potentially leading to secondary caries and pulpal irritation. Biomimetic protocols aim to provide long-term marginal sealing. When high bond strength is achieved, restoration margins do not open during function and a reliable seal is maintained for years. Particularly due to strong adhesion to dentin, the absence of gaps at the restoration margin can prevent bacteria from progressing toward the pulp and initiating the cycle leading to pulpal necrosis. This contributes to reduced

postoperative sensitivity in the patient and prolongs the lifespan of the restoration. The biomimetic approach also offers advantages regarding crack formation(Alleman et al., 2017). In the natural tooth, the flexibility of dentin limits enamel cracks; similarly, in biomimetic restorations, stress concentrations at the restoration–tooth interface can be prevented through a flexible adhesive intermediate layer and appropriate selection of elasticity. For example, one study demonstrated that, compared with conventional rigid adhesives, the use of a flexible polyurethane-based adhesive maintained greater stability of the dentin–resin interface over time and reduced microleakage under thermal stresses. These “semi-flexible” adhesives act like a shock-absorbing layer by buffering stresses originating from polymerization shrinkage and thermal changes(Zhang et al., 2020). Moreover, with the advancement of adhesive techniques, residual stress formed in the tooth after restoration can also be reduced. Residual polymerization stress may lead to cusp deformations, microgaps at the bonding interface, and ultimately cracks. The biomimetic approach aims to minimize these permanent stresses by applying stress-reducing protocols (e.g., incremental light polymerization, placement in small-volume increments, use of flexible liners, etc.).

Consequently, biomimetic restorations prevent microleakage through a strong adhesive bond while also controlling internal stresses with appropriate material selection and techniques, thereby preventing crack formation(Chandrasekhar et al., 2017).

3. BIOMIMETIC RESTORATIVE MATERIALS

3.1. Materials with dentin-like elasticity:

In biomimetic restorations, the materials used are desired to approximate the mechanical properties of dental tissues as closely as possible. Since dentin, with its semi-flexible structure, provides resilience to the tooth, materials with an elastic modulus similar to dentin play a key role in restorative success. One example developed for this purpose is polymer-infiltrated ceramic network (PICN) materials. PICN are hybrid ceramics formed by the infiltration of approximately 20–25% polymer resin into a 75–80% porcelain framework. Because this structure constitutes a graded material created by the interpenetration of two phases, it offers a combination of Young's modulus and hardness values very close to those of enamel and dentin. Indeed, researchers have succeeded in producing functionally graded PICN blocks that achieve dentin- and enamel-like differences in strength and esthetic properties within the same material(Albero et al., 2015). Similarly, fiber-reinforced composites are used to obtain restorations with elasticity close to dentin and increased crack resistance. Onlays or crowns supported with fiber-reinforced resins, instead of brittle porcelains, can reduce root fractures by mimicking the semi-flexible nature of dentin. For example, it has been reported that "fiber composite core" materials containing short glass-fiber particles exhibit compressive strength and elasticity similar to dentin and therefore can be used as a dentin substitute, particularly in large cavities(Klenner et al., 2022).

3.2. Adhesive agents and adhesive systems:

Adhesive systems and agents are among the most important developments forming the foundation of biomimetic restorations. Today, with these systems, strong bonding to both enamel and dentin can be achieved. Particularly with 4th and 5th generation total-etch adhesives, the formation of a hybrid layer in dentin has eliminated the need for macro-retention. Modern monomers such as 10-MDP provide long-lasting adhesion by forming a chemical bond with hydroxyapatite(Carrilho et al., 2019).

Some new-generation adhesives, owing to their low elastic modulus, adapt to the movement of dental tissues; this approach represents a transition from “rigid” bonding to “flexible” adhesion. Moreover, the hydrophilic nature of adhesives and the wet bonding technique facilitate deep penetration of resin monomers into dentin by preventing collapse of the collagen fibers(Alleman et al., 2017). The resulting hybrid layer forms a strong and flexible connection between the tooth and the restoration that mimics the natural dentino-enamel junction. In this way, biomimetic restorations function in an integrated manner with dental tissues and provide long-term durability.

3.3. Resin composites, glass ionomers, and ORMOCERs:

Composite resins and glass ionomer cements (GICs) are the most common tooth-colored restorative materials. Composite resins consist of an organic polymer matrix and inorganic filler particles and

mimic the organic–inorganic structure of the natural tooth. These materials, used since the 1960s, offer advantages in terms of esthetics, biocompatibility, and ease of application. Today, nano-filled composites have been developed to separately mimic dentin and enamel layers. In addition, research on self-healing composites has demonstrated that repair can occur through the release of monomers from microcapsules when a crack forms(Ferracane, 2024; Sidhu & Nicholson, 2016).

Glass ionomer cements are described as “artificial dentin” because they chemically bond to dental tissues and release fluoride. Owing to their thermal expansion coefficients being close to that of the tooth, they behave compatibly during temperature changes and reduce microleakage. Resin-modified and nano-filled new-generation types are more durable than conventional GICs(Sidhu & Nicholson, 2016).

ORMOCERs (Organically Modified Ceramics) are advanced composites formed by the combination of organic polymers with an inorganic silica network. These materials offer lower polymerization shrinkage and better biocompatibility compared with conventional methacrylate-based composites. New-generation nano-hybrid ORMOCER composites stand out in modern restorative applications in terms of both esthetics and durability(Kalra et al., 2012).

In conclusion, the aim in biomimetic dentistry is to use materials that exhibit physical and chemical properties as close as possible to those of dental tissues. Composites, glass ionomers, and ORMOCERs

are the principal restorative materials that serve this purpose by mimicking nature.

3.4. Biomimetic ceramics:

Ceramic-based restoratives are indispensable in dentistry because, together with their esthetic superiority, they provide surface characteristics close to those of natural tooth structure. From a biomimetic perspective, an ideal dental ceramic should not only replicate the appearance of enamel but also mimic the mechanical properties and function of both enamel and dentin(Magne, 2006). Research has been conducted for many years in pursuit of this goal. For example, Holland et al. developed an apatite–leucite glass ceramic in 2000; this ceramic contains needle-shaped hydroxyapatite crystals similar to those found in natural hard dental tissues. Owing to this needle-like crystal structure, significant improvements were achieved in the material's esthetic and mechanical properties(Ho¨ land et al., 2000). Another innovation in the field of biomimetic ceramics is bioactive ceramics. Ideally, a biomimetic ceramic should be able to adhere to dental tissues without leaving gaps and support the self-repair mechanisms of the surrounding tissues(Singer et al., 2023). Indeed, Goudouri et al. endowed a commercial dental ceramic with an apatite-coating capability, enabling the formation of a hydroxyapatite layer on the material's surface. As a result, when the ceramic restoration was applied to the tooth surface, it created an interface that self-bonded to the dental tissue via apatite formation, thereby increasing sealing ability and potentially promoting regeneration of the surrounding

tissues(Goudouri et al., 2014). Recently popular multilayer zirconia blocks are also produced according to biomimetic principles: these blocks incorporate different types of zirconia layers within a single structure. In the lower portion, high-strength opaque 3Y-TZP is present, while at the occlusal surface a more translucent and tougher 5Y-TZP is used, thereby providing dentin-like strength and enamel-like esthetics within a single restoration(Michailova et al., 2020). This concept aims to mimic the function of the different layers of the tooth within a single restoration by creating a structurally graded restoration. In summary, the biomimetic approach in ceramic restorative materials focuses on enabling these materials to function similarly to dental tissues by imparting natural-like properties at the microstructure level (crystal arrangement), macrostructure level (multilayer blocks), and surface chemistry level (bioactive coatings).

4. SIMULATION AND PRESERVATION OF BIOMIMETIC TOOTH STRUCTURE

4.1. Simulation of the actual dentin structure:

In the restoration of large cavities or in cases where a significant portion of the crown has been lost, mimicking the dentin structure is critical to ensure that the restoration behaves like a natural tooth. In current biomimetic restorative approaches, the lost dentin mass of the tooth is reconstructed using special techniques referred to as a “biobase.” For example, an artificial dentin layer can be created by applying a fiber-reinforced composite base layer that integrates

compatibly with the remaining tooth walls. This base layer behaves semi-flexibly like dentin and supports the harder restorative material placed above it. Subsequently, a final layer material that mimics enamel (e.g., a porcelain laminate or enamel composite) is placed over this base. In this way, the layered restoration simulates both the internal and external structure of the tooth(Klenner et al., 2022). Layering techniques developed by pioneers such as Pascal Magne aim to replicate all visual characteristics of the tooth from deep dentin to surface enamel by using composites of different shades and opacities. However, layering is also important functionally: the dentin composite placed in the inner layer, being softer and more opaque, mimics the translucency and flexibility of dentin, whereas the enamel composite placed in the outer layer provides a hard and glossy surface, mimicking enamel. In this way, the restoration behaves similarly to the tooth not only in color but also in stress distribution during mastication(Magne, 2006; Ricci & Fahl Jr, 2023). Another dimension of biomimetic simulation is the modeling of tooth structure through digital design and analysis techniques. In recent years, methods such as finite element analysis have been used to model dental tissues and restorations together and to examine stress distributions. These analyses allow prediction of, for example, the effect of the thickness of a liner placed beneath a filling or the influence of restoration shape on stresses. The obtained data are guiding in reflecting real dentin behavior in the restoration(Gönder et al., 2023). In conclusion, the concept of simulating the real dentin structure encompasses material selection, layering, and digital design techniques, all aimed at enabling the

restoration to function as if it were the tooth's own dentin. When achieved, especially in large restorations, the restoration will flex and bear loads together with the tooth, thereby minimizing problems such as debonding and dislodgement.

4.2. Fracture management and microfracture prevention:

Cracked teeth or situations carrying a risk of fracture are conditions to which the biomimetic approach gives special attention. If a tooth has an existing crack (for example, in a case of cracked tooth syndrome), the conventional solution is often to encircle the tooth with a full crown. The biomimetic approach, however, generally aims to control the crack with more conservative methods. First, special adhesive techniques are applied to prevent progression of the crack line. The crack can be "frozen" by opening a fine fissure along it and applying a low-viscosity resin infiltrant inside. This procedure halts crack propagation by bonding the crack surfaces together. In larger cracks, fiber strips and composite splints are applied around the tooth, effectively creating a clamping effect. In this way, the crack cannot widen during mastication and the tooth fragments are kept together(Kakka et al., 2022). The biomimetic concept also aims to prevent crack formation by preserving the natural flexibility of the tooth. For example, when placing very large composite restorations, filling the cavity in small increments (incremental technique) and polymerizing each layer separately, rather than filling the entire cavity in a single mass, reduces the risk of microcracks caused by polymerization shrinkage(Alleman et al., 2017). Additionally, fibers

placed within the composite or the use of low-modulus liners can absorb incipient microcracks by distributing stresses(Singer et al., 2023). Another important point is the quality of the adhesive bond: the better the restoration adheres to the tooth, the fewer gaps remain at the interface and no weak points are left for crack formation. The technique known as Immediate Dentin Sealing (IDS) involves sealing the prepared dentin immediately with an adhesive. In this way, bacterial leakage into dentin or crack formation during the provisional restoration period is prevented, and when the final restoration is placed, a strong dentin bond already exists. It has been shown that teeth treated with IDS exhibit reduced postoperative sensitivity and better marginal adaptation compared with untreated teeth(Alleman et al., 2017). All these measures are intended to prevent the formation of microcracks from the outset. In conclusion, the biomimetic approach adopts both proactive and therapeutic strategies in crack management. Existing cracks are stabilized and arrested with adhesive techniques, while the formation of new cracks is prevented through minimally invasive preparations, stress cushioning, and strong adhesive bonding. In this way, the structural integrity of the tooth is preserved in the long term and the patient may be spared unnecessary endodontic treatments or extractions.

4.3. Application of "layering" techniques based on biomimetic principles:

Layering in esthetic and restorative dentistry has long been used to mimic enamel and dentin opacities. In biomimetic dentistry, however, layering is applied not only for esthetics but also for the

mechanical performance of the restoration. The fundamental idea is the sequential reconstruction of natural tooth layers. For example, in the restoration of an anterior tooth, an opaque and flexible composite resin that imitates the dentin region is first placed, followed by a translucent and harder composite that mimics enamel on the surface. Together, these two layers reflect and refract light like a natural tooth and also withstand forces in a similar manner. Layering techniques are used not only in direct composite restorations but also in indirect restorations. When modern porcelain laminate veneers or ceramic onlays are fabricated, technicians apply dual or triple ceramic powders in the laboratory to create dentin and enamel layer effects. A more opaque dentin ceramic is applied internally, and a translucent enamel ceramic is placed on the outer surface. This approach increases color depth and produces a lifelike appearance while simultaneously benefiting from the different mechanical properties of the layers. Another dimension of biomimetic layering is the control of polymerization shrinkage. In stress-reduced layering protocols, instead of placing a large composite mass into the cavity at once, the restoration is built in multiple small segments. For example, restoring a 4-mm-deep cavity in two or three increments allows each portion to shrink separately and transfer less stress to the others. The “stress-reduced direct composite” technique described in 2002 reported a 30–40% reduction in polymerization stress and a three- to fourfold increase in dentin bond strength based on this principle. The resulting strong bond and low residual stress facilitate restoration behavior similar to that of a natural tooth(Alleman et al., 2017). In summary, the biomimetic application of layering techniques

means replicating the natural construction of the tooth while building a restoration. If each layer is applied with the appropriate material and in the correct sequence, the resulting structure will not be a monoblock filling but a multilayered artificial tooth tissue. This provides superiority of the restoration in both esthetic and functional aspects. For patients, this means that their restorations not only appear more natural but are also longer-lasting and more tooth-friendly.

5. THE ROLE OF ADHESIVE SYSTEMS

5.1. Elastic modulus compatibility:

The adhesive layer between the tooth and the restoration constitutes the backbone of biomimetic restorations. Adjusting the elastic modulus of adhesive systems to be compatible with dental tissues is an important objective. Because enamel is very hard and dentin is softer, direct bonding of a rigid composite to dentin creates a significant elasticity mismatch. For this reason, modern adhesive approaches recommend leaving an adhesive layer that functions as a "stress breaker" between the composite and dentin. A thin adhesive film layer or flowable resin can absorb shrinkage stress by flexing slightly during polymerization(Ausiello et al., 2002). A study demonstrated that a low-elastic-modulus adhesive containing flexible polyurethane oligomers increased dentin bond strength after thermal cycling and reduced microleakage compared with standard rigid adhesives. This finding emphasized the importance of a connection capable of slight flexion rather than a completely rigid bond. Matching the elasticity of

the adhesive to that of dentin homogenizes force transmission and prevents stress concentration at the bonding interface that could lead to failure. Some filled adhesive systems (e.g., seventh-generation adhesives containing nanoparticles), when applied in a thicker layer, behave almost like a thin intermediate composite layer and create a cushioning effect during polymerization shrinkage(Zhang et al., 2020). Resin-modified glass ionomer liners placed on the cavity floor similarly behave close to dentin because of their low modulus, dissipating the stress of the overlying composite without damaging the dentin. The common objective of all these applications is to maximize the mechanical compatibility between dental tissue and the adhesive. When elastic modulus compatibility is achieved, the restoration–tooth complex bears load as a single unit and no weak link remains at the interface. Consequently, through proper selection and application of adhesive systems, the connection of the restoration to the tooth exhibits a structure that is neither too rigid nor too flexible, achieving biomimetic integration.

5.2. Biomimetic bonding techniques:

In biomimetic dentistry, not only which adhesive is used but also how it is used is critically important. Immediate Dentin Sealing (IDS) is considered one of the cornerstones of biomimetic bonding. In the IDS technique, immediately after tooth preparation, all exposed dentin surfaces are isolated with an appropriate adhesive. This ensures immediate sealing of the dentinal tubules and prevents bacterial leakage and the development of sensitivity. Moreover, because resin infiltration

is optimal in freshly cut dentin, very strong bonding is achieved when the final restoration is placed in teeth treated with IDS. This technique, particularly in indirect restorations (onlays, crowns, etc.), prevents saliva contamination of dentin during the waiting period, thereby minimizing microleakage and virtually eliminating postoperative sensitivity(Alleman et al., 2017). Another key aspect of biomimetic bonding is adhesive surface preparation. Traditionally, "etch-and-rinse" (total-etch) and "self-etch" protocols have been used. The biomimetic approach selects the appropriate method according to the case; for example, strong phosphoric acid etching on enamel surfaces exposes enamel prisms and provides excellent retention, whereas self-etch agents may be preferred in dentin where excessive etching could weaken collagen. The goal is to achieve a combination of micromechanical retention in enamel and chemical adhesion in dentin, similar to the mechanism of the natural DEJ: strong microretention on the enamel side and a transition on the dentin side where chemical and mechanical bonding coexist(Tran & Tran, 2021). Modern universal (multi-purpose) adhesives, through monomers such as 10-MDP in their composition, can form a chemical bond with calcium, allowing good adhesion to dentin even without acid treatment, comparable to that achieved on acid-etched enamel. A two-step bonding approach may also be considered a biomimetic technique: first, primer and adhesive are applied to dentin and polymerized, and then an additional adhesive interface is created during restoration cementation. With this dual-stage approach, the quality of the hybrid layer increases and the adverse effects of shrinkage stresses are reduced(Carrilho et al., 2019). Another

important aspect of biomimetic bonding relates to cavity design: instead of traditional cavities with straight walls and sharp angles, rounded margins and gradual cavity forms are preferred. Sharp corners may lead to stress concentration, whereas rounded preparation margins allow the adhesive resin to wet the area more effectively and create a homogeneous bond. Additionally, in situations with a high C-factor, adhesive bonding is supported by incremental polymerization or the use of liners to reduce the resulting stress. All these technical details ultimately aim at achieving perfection in the adhesive bond, because the success of a biomimetic restoration depends on the tooth and restoration integrating almost at the molecular level(Hubsch et al., 2002). To achieve this, contemporary bonding techniques must be applied meticulously, manufacturer instructions must be strictly followed, and the tooth surface must be clean and at optimal moisture. In conclusion, biomimetic bonding techniques are scientifically grounded, precise protocols developed to create a bond that does not disrupt the natural structure of the tooth but rather reinforces it.

5.3. The importance of chemical binding in replacing micro and macro retention:

In classical restorative applications, the shape of the cavity was of great importance to keep the filling in place. Whereas today, thanks to adhesive technologies, the importance of cavity geometry has decreased and the importance of chemical/adhesive retention has increased. This represents a true paradigm shift in dentistry. As Michael Buonocore stated in the 1950s, “a restorative material capable of

strongly bonding to tooth structure would offer great advantages over existing methods; with such a material, retention and resistance form in cavity preparation would no longer be necessary," a prediction that has now become reality(Buonocore, 1955). Thanks to acid etching and adhesive resins, practices such as dovetail-type cavity retention forms or carving coronal grooves and shoulders in crowns have been minimized. Especially in minimally invasive approaches, the essential principle is to remove caries while preserving healthy tooth structure as much as possible; with adhesives, it is no longer necessary to sacrifice sound tooth tissue for "retention." In this context, the principle of prevention of extension has replaced the concept of extension for prevention(Burke, 2003). For example, with older amalgam restorations it was necessary to prepare a box form of specific depth and width; otherwise the filling could dislodge. Today, when an adhesive composite is placed even into a small cavity, it bonds to enamel via acid etching and to dentin via primer and bonding agent, remaining highly stable. Another example is indirect restorations such as inlays/onlays: whereas divergent walls and mechanical retention features such as gold foils were once required, today the opposite preparations with convergent walls and even slight undercuts can be successfully restored with adhesive cementation. Macro-retentive elements (e.g., amalgam pins, root posts, box forms) are, in most cases, traumatic for the tooth and contrary to the biomimetic philosophy. With the development of adhesive dentistry, most of these have been abandoned. Studies have shown that a good adhesive bond alone is sufficient to retain a restoration, and that adding additional mechanical retention often

disrupts stress distribution and may create harmful effects(Alleman et al., 2017). For example, when a fiber post is fixed with adhesive cement, the benefit provided by the post is debatable; in fact, bonding of the cement to dentin alone is sufficient to protect the tooth, whereas the post may only increase intraradicular stresses. For this reason, a "postless structure" has begun to be preferred in many cases(Alshabib et al., 2023).

6. CONCLUSION

Biomimetic dentistry represents the most advanced stage reached by modern restorative practice, as it aims not only to repair damaged tissue but also to reestablish the biological, mechanical, and esthetic integrity of the tooth. Material selection that mimics the natural structure of enamel, dentin, and the enamel–dentin complex; adhesive strategies that absorb stress during function; multilayer composite and ceramic applications; and digital analysis methods enable the restoration to function as a single unit with the tooth. Through this approach, unnecessary tissue loss is prevented, microleakage and crack formation are minimized, and the longevity of restorations is significantly extended. Furthermore, finite element analyses and advanced simulation techniques allow restoration design to be grounded on scientific principles, making it possible to develop biomechanically safer treatments. From crack management to adhesive protocols, and from materials science to digital design, all these components serve the same common objective: to preserve, strengthen,

and maintain the natural balance of form and function of the tooth at the highest level.

In conclusion, the biomimetic restorative approach is not merely a technical method but the clinical embodiment of the philosophy of "healing by imitating nature" in dentistry, forming the foundation of future minimally invasive, long-lasting, and patient-friendly treatments.

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CHAPTER 2

DENTAL OCCLUSION ASSESSMENT METHODS IN PEDIATRIC DENTISTRY

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INTRODUCTION

Occlusion in pediatric dentistry is directly related to craniofacial structures during the growth and development period and is one of the fundamental factors determining jaw development and dental balance. The proper formation of occlusion during childhood ensures both the healthy development of masticatory function and the prevention of orthodontic and functional problems that may occur in later years (Proffit et al., 2018). Occlusal irregularities arising during early childhood may lead to malocclusion and result in long-term effects such as temporomandibular joint disorders, functional chewing disorders and speech abnormalities (Rosa et al., 2012). Therefore, early assessment of occlusion in children and implementation of appropriate preventive or corrective treatments are essential.

1. Methods for Dental Occlusion Assessment

Occlusion refers to the functional contact relationship between the maxillary and mandibular teeth and should be evaluated in both static and dynamic conditions. Currently, both conventional and digital methods are used to assess dental occlusion. Each method has its own

advantages and limitations, and the appropriate technique should be selected according to the clinical objectives (Koos et al., 2010; Kerstein et al., 2020).

1.1. Conventional Methods

Conventional methods allow only the localization of occlusal contact points; however, they do not provide information regarding the sequence, duration or force intensity of these contacts. These methods yield only qualitative data and the presence of contacts largely depends on the clinician's subjective interpretation. Additionally, repeated use of these materials and their exposure to intraoral fluids may reduce their accuracy in detecting occlusal contact points (Saraçoğlu and Özpınar, 2002; Ries et al., 2022).

Commonly used conventional occlusal analysis materials include articulating papers, silicone bite registration materials, metallic foils, silk strips and occlusal sprays (Saraçoğlu and Özpınar, 2002; Kerstein and Radke, 2014; Qadeer et al., 2021).

However, studies in the literature have demonstrated that none of these conventional methods are capable of quantifying occlusal force magnitude, determining contact duration or identifying the sequence of tooth contacts occurring during closure until maximum intercuspation is reached (Kerstein, 2008; Koos et al., 2010).

1.1.1. Articulating Papers

Articulating papers are among the most commonly used conventional materials for identifying the localization of occlusal contact points (Bozhkova et al., 2021). Carbon papers, typically available in red and blue colors, can be used to detect both static and

functional contacts (Figure 1). However, findings obtained with this method provide only qualitative information regarding the presence of contact and do not allow evaluation of parameters such as contact duration, sequence, or force magnitude (Qadeer et al., 2012). The subjective nature of interpretation and the potential loss of sensitivity due to exposure to intraoral fluids are among the main limitations of this method (Afrashtehfar and Qadeer, 2016; Beninati and Katona, 2019; Sutter, 2019).

Figure 1: Articulation papers in various colors and shapes

1.1.2 Metallic Foil

Metallic foil consists of transparent or metallic strips with a thickness of 8–12 microns and is used to detect the presence of occlusal contact (Qadeer and Sarinnaphakorn, 2019). This method determines contact based on whether the strip can pass between opposing teeth (Harper and Setchell, 2002). However, similar to articulating paper, it does not allow measurement of force magnitude or determination of the sequence of contacts. Due to its inability to provide quantitative data

and its limitation to indicating only the presence or absence of contact, it is considered a limited assessment tool (Sharma et al., 2013).

1.1.3 Alginate or Silicone-Based Occlusal Records

Alginate or silicone-based materials are used to record the patient's interocclusal relationships and transfer this relationship to an articulator (Figure 2). When used in conjunction with a facebow and articulator, this method allows a three-dimensional and detailed analysis of occlusal guidance (Tejo et al., 2012). However, the length of the procedure, time requirements and high operator dependency represent important limitations of this method. Therefore although it provides advantages in terms of anatomical accuracy, its practical clinical use requires careful planning (Sharma et al., 2013; Thanabalan et al., 2019).

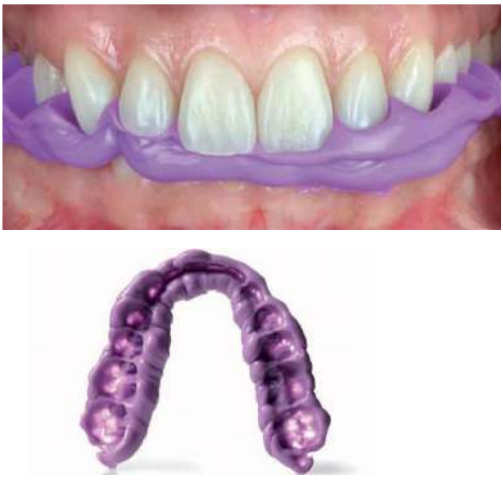

Figure 2: Silicone- based occlusal closure record

1.2 Digital Methods

Unlike conventional methods, which focus solely on the presence of occlusal contact points, digital systems provide quantitative analysis by displaying the sequence, duration, and force distribution of occlusal contacts. While traditional methods offer limited assessment based on subjective interpretation, digital systems enable objective analysis of the temporal and spatial characteristics of occlusal contacts (Kerstein, 2020; Zhang et al., 2024). In particular, computer-assisted occlusal analysis systems utilize pressure-sensitive sensor films in combination with dedicated software to visualize the distribution of occlusal forces and contact dynamics in detail. Among these systems, digital analysis devices such as T-Scan and OccluSense, as well as the integrated use of CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) technologies, have become one of the most frequently preferred approaches for evaluating occlusal relationships in contemporary clinical practice (Kerstein, 2008; Koos et al., 2010)

1.2.1 T-Scan Occlusion Analysis System

The T-Scan digital occlusal analysis system is a computer-assisted system that enables quantitative and objective evaluation of occlusion in multiple parameters where conventional methods remain insufficient (Maness et al., 1987). First introduced in 1987, the system has become increasingly widespread in both clinical and research settings due to continuous advancements in software and sensor technology (Lyons et al., 1992; Kerstein, 2008; Koos et al., 2010; Kerstein et al., 2013). The T-Scan system consists of a high-resolution thin sensor plate, a USB interface module, and dedicated analysis

software (Figure 3). Using a pressure-sensitive sensor approximately 60–100 µm thick, the system records all occlusal contacts occurring during mandibular closure at the millisecond level. The collected data are displayed visually through color-coded graphical outputs within the software interface, allowing detailed analysis of occlusal load distribution on individual teeth, as well as the sequence and duration of occlusal contacts (Korioth, 1990; Garcia et al., 1997; Baba et al., 2000; Kerstein & Radke, 2014).

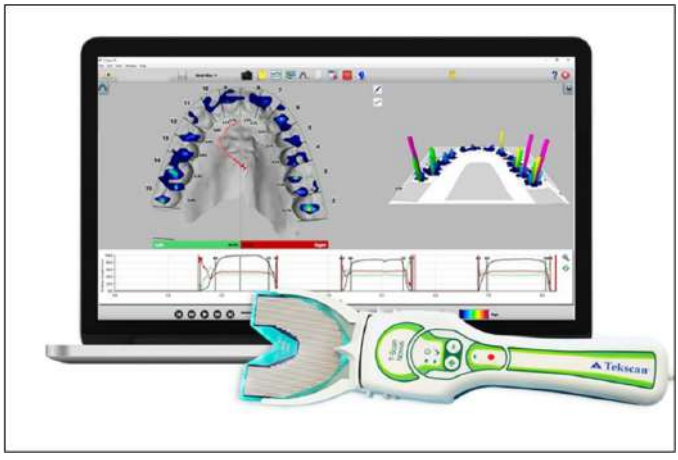

Figure 3: T Scan digital occlusal analysis system

One of the major advantages of this system is that it not only identifies the presence of occlusal contacts but also evaluates their force magnitude and sequence. This enables the objective detection of clinically critical conditions such as premature contacts, overloaded teeth, and occlusal interferences, thereby allowing more precise treatment planning (Bathiya, 2020).

However, the T-Scan system also has certain limitations. The sensors have a finite lifespan and may lose sensitivity over time, which can affect measurement accuracy (Wang et al., 2022; Chowdhary & Sonnahalli, 2024). In addition, measurements are primarily performed in the maximum intercuspal position, and contacts occurring during lateral or protrusive movements require indirect evaluation. The relatively high cost of the device and the need for user training are also factors that limit its widespread clinical use (Wang et al., 2022). Nevertheless, considering its ability to provide objective, dynamic, and reproducible data, the T-Scan system stands out as one of the digital technologies with strong potential to serve as a gold standard in occlusal analysis (Koos et al., 2010; Sutter & Rettie, 2019; Dias et al., 2020).

1.2.2. Digital Scanners and Virtual Articulators

With recent advances in digital technologies, three-dimensional (3D) digital scanners and virtual articulator systems have become increasingly important in occlusal analysis. These systems enable three-dimensional modeling of occlusal contacts, providing a level of detailed visualization that cannot be achieved with conventional methods (Figure 4). Virtual articulator software can simulate mandibular movements based on patient-specific records, thereby allowing the analysis of occlusal guidance and contact dynamics within a digital environment.

Figure 4: 3D intraoral digital scanners and virtual articulators

1.2.3. OccluSense Occlusion Analysis System

OccluSense (Dr. Jean Bausch GmbH & Co., Cologne, Germany) is a digital occlusal analysis system developed in 2019 to determine occlusal contacts and occlusal force distribution (Sutter & Rettie, 2019). The system consists of a sensor, a sensor holder, and computer software. The OccluSense sensor is a thin foil, only 60 µm thick, coated with red dye and containing printed electronics with 1,018 pressure-sensitive pixels capable of detecting 256 pressure levels. Its thin and flexible structure enables the recording of occlusal contacts both under low-pressure conditions and during dynamic mandibular movements (Popa & Ahler, 2024).

Data are recorded using a handheld device and transferred wirelessly to the OccluSense application (Figure 5). The clinician can visualize the recorded data through two-dimensional (2D) and three-dimensional (3D) graphical displays and evaluate occlusal load distribution as percentages. The OccluSense system presents the occlusal analysis of the entire dental arch using color-coded representations.

Figure 5: OccluSense device and iPad app (https://www.prestige-dental.co.uk/product/bausch-occlusense-electronic-pressure-sensor/)

One of the main advantages of OccluSense is its ability to visualize occlusal force distribution in real time (Uğurgelen, 2022; Çavuşculu Güldül, 2025). This enables the precise identification of premature contacts and regions subjected to excessive force, thereby allowing more accurate occlusal adjustments. Consequently, both masticatory function can be optimized and patient comfort can be improved (Çavuşculu Güldül, 2025). Compared with conventional

methods, OccluSense provides a significant advancement by offering not only qualitative assessments but also detailed visual and quantitative data (Sutter & Rettie, 2019; Aung & Nyan, 2022). These digital records can be archived and used as reference data during future clinical evaluations.

In addition, the articulating paper integrated into the sensor allows direct marking of occlusal contact points on the tooth surfaces during measurement (Popa & Ahler, 2024; Çavuşculu Güldül, 2025). However, accurate interpretation of these digital data requires careful analysis of the recorded datasets independently of the marked contact areas. Furthermore, the single-use design of the sensor, as recommended by the manufacturer, is considered a limitation of the system (https://tr.occlusense.com, accessed August 25, 2024).

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CHAPTER 3

DISSOCIATION BETWEEN CLINICAL PARAMETERS AND PATIENT-CENTERED OUTCOMES IN PERIODONTAL DISEASES: A BIOLOGICAL AND BEHAVIORAL PERSPECTIVE

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PREFACE

Periodontal diseases are multifactorial health conditions that extend beyond the biological destruction of the supporting tissues surrounding the teeth. They represent complex disorders that may significantly influence an individual's functional capacity, psychological well-being, and social life. Although the clinical evaluation of periodontal diseases has traditionally relied on objective clinical parameters for many years, contemporary literature increasingly emphasizes that this approach does not always fully reflect the true burden of the disease experienced by individuals.

This book chapter aims to address the relationship between clinical periodontal parameters and patient-centered outcomes within a comprehensive and integrative framework. In addition to the biological indicators that define periodontal inflammation and tissue destruction, the chapter discusses how the concept of oral health–related quality of life can be integrated into periodontal assessment. In this context, the biological, behavioral, and psychosocial

foundations underlying the dissociation between clinical measurements and the perceived burden of disease are examined in light of current scientific evidence.

The chapter systematically presents the biological basis and measurement limitations of clinical periodontal parameters, the theoretical framework of patient-reported outcome measures, the potential causes of discrepancies between clinical findings and patient perception, and the determining role of education and behavior in periodontal health. The primary objective is to promote a patient-centered perspective in periodontal evaluation that considers not only clinical improvement but also changes in individuals' quality of life.

This chapter is intended to serve as a guide for clinicians who seek to incorporate patient-centered measures into clinical decision-making processes, as well as for researchers planning to utilize patient-reported outcome measures in periodontal research.

By addressing both clinical and patient-centered assessments together, this integrated approach may contribute to a more sustainable and holistic framework for periodontal diagnosis and treatment. Accordingly, the following sections examine the relationship between clinical evaluation approaches in periodontal diseases and patient-reported outcomes from both biological and behavioral perspectives.

1. INTRODUCTION

Periodontal diseases are chronic, multifactorial conditions characterized by inflammatory destruction of the tissues surrounding and supporting the teeth.(Lang & Bartold, 2018; Papapanou et al., 2018) In clinical practice, measurable clinical parameters such as the plaque index, gingival index, probing pocket depth, and clinical attachment loss have long been used as fundamental tools for the diagnosis and monitoring of periodontal diseases. These parameters aim to objectively reflect biological changes occurring in the periodontal tissues and play a guiding role in treatment planning. (AlJasser et al., 2023; Sabrina Lill Buset et al., 2016; Löe, 1967)

However, it has become increasingly evident that improvements observed in clinical parameters following periodontal treatment do not always parallel patients' perceptions of their oral health or their experiences in daily life. Even in cases considered clinically successful, patients may report pain, functional limitations, aesthetic concerns, and psychosocial discomfort. Conversely, in some individuals, significant impairments in quality of life have been reported despite relatively limited clinical findings.(Haag et al., 2017; Pawar, Puranik, & Shanbhag, 2022; Reissmann et al., 2019) This situation suggests that periodontal diseases represent complex processes involving not only biological mechanisms but also perceptual and behavioral dimensions.

The concept of oral health–related quality of life (OHRQoL) aims to evaluate the impact of individuals' oral health status on their physical, psychological, and social well-being from a subjective

perspective.(João Botelho et al., 2020) This approach provides a complementary perspective to clinical indicators in revealing the true burden of periodontal diseases on patients. In this context, the Oral Health Impact Profile (OHIP), and particularly its short form OHIP-14, are among the most widely used patient-centered assessment tools for measuring the impact of periodontal diseases on individuals' quality of life.

A review of the existing literature indicates that a strong and linear relationship does not always exist between periodontal clinical parameters and OHRQoL measurements.(J. Botelho et al., 2020; Montero et al., 2021; Vogt et al., 2023) Among the factors underlying this dissociation are the perceptual dimension of inflammation, pain threshold, individual expectations, educational level, psychosocial factors, and behaviors related to oral health. In particular, it has been suggested that increased knowledge levels, clinical experience, and awareness among healthcare professionals may shape the relationship between periodontal findings and patient perception.(Armencia et al., 2023)

This chapter aims to examine the structural dissociation between clinical parameters and patient-centered outcomes in periodontal diseases within a biological and behavioral framework. Current evidence suggests that approaches focusing solely on clinical improvement may not fully reflect the overall success of periodontal treatment. Therefore, integrating clinical indicators with patient-centered measurements in the evaluation of periodontal

diseases has the potential to provide a more comprehensive approach for both clinical practice and future research.(Tonetti et al., 2025)

2. CLINICAL PERIODONTAL PARAMETERS: BIOLOGICAL BASIS AND MEASUREMENT LIMITATIONS

Clinical periodontal parameters are widely used as fundamental assessment tools for the diagnosis, staging, and monitoring of periodontal diseases. The plaque index (PI), gingival index (GI), probing pocket depth (PPD), and clinical attachment loss (CAL) aim to quantitatively reflect the level of inflammation in periodontal tissues, the microbial burden, and the destruction of supporting structures. These parameters represent indirect indicators of the biological activity of periodontal disease and have long been accepted as standard measures in both clinical practice and epidemiological studies. (Lang & Bartold, 2018; Papapanou et al., 2018; Tonetti, Greenwell, & Kornman, 2018).

The plaque index (PI) evaluates the amount of microbial biofilm accumulated on tooth surfaces and thereby reflects the primary etiological factor of periodontal inflammation. The presence of dental plaque acts as the main stimulus that triggers the host response and plays a critical role in initiating the inflammatory reaction in gingival tissues.

The gingival index (GI), on the other hand, assesses the clinical signs of inflammation in gingival tissues, particularly through changes in color, edema, and the presence of bleeding upon probing. These two indices demonstrate high sensitivity in detecting

the inflammatory process during the early stages of periodontal disease.(Löe, 1967; Marsh & Bradshaw, 1995).

Probing pocket depth (PPD) and clinical attachment loss (CAL) are fundamental parameters used to evaluate the progressive nature of periodontal disease and the extent of destruction in the supporting tissues. While PPD reflects the depth of the gingival sulcus or periodontal pocket, CAL represents the actual loss of periodontal attachment by considering both gingival recession and pocket depth together. These parameters are particularly critical for disease staging and for determining the prognosis.(Armitage, 1999; Caton et al., 2018).

However, clinical periodontal parameters have several important limitations. Although these measurements reflect the extent of tissue damage in the periodontal structures, they do not directly provide information about the biological activity of the disease, individual pain perception, functional limitations, or psychosocial impacts. Moreover, the severity of periodontal inflammation does not always show a linear relationship with an individual's perception of symptoms. As a result, individuals with clinically similar periodontal findings may exhibit considerable differences in their perceived disease burden and quality of life.(S. L. Buset et al., 2016; Needleman et al., 2005; Trindade et al., 2023).

In recent years, the need to consider clinical parameters in periodontal disease classifications together with biological and prognostic information has been increasingly emphasized. The staging and grading system proposed at the 2017 World Workshop

on the Classification of Periodontal and Peri-Implant Diseases and Conditions introduced a more dynamic approach to clinical evaluation by taking into account not only disease severity but also the rate of progression and associated risk factors. However, even this contemporary classification does not directly reflect patients' subjective experiences related to oral health or the impact of the disease on their quality of life.(Tonetti, Greenwell, & Kornman, 2018; Trindade et al., 2023).

In this context, clinical periodontal parameters are indispensable for defining the biological dimension of periodontal diseases; however, they are not sufficient on their own to reveal the true impact of the disease burden on the patient. Considering clinical indicators together with patient-centered assessment tools may allow periodontal diseases to be evaluated within a more comprehensive framework that better reflects clinical reality.(M. Sanz et al., 2020).

3. PATIENT-CENTERED OUTCOMES: THE THEORETICAL FRAMEWORK OF OHRQOL AND OHIP-14

Traditional approaches to periodontal assessment aim to objectively evaluate the biological and clinical dimensions of disease through measurable parameters. However, the true impact of periodontal diseases on individuals is not limited to clinical findings alone; it also encompasses multidimensional consequences, including effects on daily activities, psychological well-being, and social interactions.

In response to this need, patient-reported outcomes (PROs) have been developed and are increasingly recognized as important tools for assessing the perceived burden of periodontal diseases from the patient's perspective.(Black, 2013; Weldring & Smith, 2013).

The concept of oral health–related quality of life (OHRQoL) addresses the impact of an individual's oral health status on functional, psychological, and social aspects of life from a subjective perspective. By aiming to bridge the gap between clinical findings and individuals' lived experiences, the OHRQoL approach provides an opportunity to evaluate the impact of periodontal diseases on patients within a more comprehensive framework.

In this context, it has been demonstrated that periodontal diseases may influence quality of life not only through tissue destruction but also through factors such as pain perception, aesthetic concerns, and difficulties in speaking and eating.(P. F. Allen, 2003; Locker, 1988).

One of the most widely used instruments for measuring OHRQoL is the Oral Health Impact Profile (OHIP), which was developed by Gary D. Slade and A. John Spencer to evaluate individuals' life experiences related to oral health. The original OHIP scale consists of 49 items; however, the OHIP-14, developed as a shorter version to facilitate more practical use in clinical and epidemiological studies, is a validated and reliable short-form instrument.(Slade, 1997; Slade & Spencer, 1994). The OHIP-14 evaluates the impact of oral health on individuals' lives across seven domains: functional limitation, physical pain, psychological

discomfort, physical disability, psychological disability, social disability, and handicap.

The theoretical foundation of the OHIP-14 is based on the assumption that oral health problems produce not only biomedical consequences but also psychosocial outcomes. This perspective acknowledges that a linear relationship does not always exist between the severity of periodontal disease and the quality-of-life impacts reported by individuals. Indeed, the literature indicates that individuals with clinically similar periodontal findings may exhibit considerable differences in their OHIP-14 scores.(João Botelho et al., 2020; De Rubertis et al., 2025; Montero et al., 2021) This observation suggests that individual perception, expectations, educational level, and coping mechanisms play a determining role in OHRQoL.

In individuals with periodontitis, OHIP-14 scores have been reported to increase particularly with greater gingival inflammation, bleeding, and functional limitations. Conversely, significant improvements in quality-of-life scores have been observed following periodontal treatment. (Needleman et al., 2004; Ng & Leung, 2006; Shanbhag, Dahiya, & Croucher, 2012). These findings indicate that the OHIP-14 is a sensitive measurement tool that reflects not only the burden of disease but also the effectiveness of treatment from a patient-centered perspective. However, as a short-form instrument, the OHIP-14 also has certain limitations, such as the potential inability to capture some individual experiences in sufficient detail.(Reissmann et al., 2019)

In recent years, a strong consensus has emerged in the periodontal literature emphasizing that clinical parameters should be evaluated alongside patient-centered measures. This approach proposes that the success of periodontal treatment should not be assessed solely on the basis of clinical improvement, but also in relation to changes in an individual's functional, psychological, and social well-being.(Tonetti et al., 2025). In this context, the OHIP-14 has emerged as an important assessment tool in periodontal research and clinical practice, complementing traditional clinical indicators.

4. WHY DO CLINICAL FINDINGS AND PATIENT PERCEPTION DIVERGE? BIOLOGICAL AND BEHAVIORAL EXPLANATIONS

The discrepancy between clinical parameters and patient-reported outcomes in periodontal diseases can be explained by the fact that the condition is not limited solely to tissue-level inflammation and destruction. While clinical measures quantitatively reflect the biological aspects of periodontal disease, an individual's experience of illness is shaped by the interaction of pain perception, functional limitations, aesthetic concerns, and psychosocial determinants.(P Finbarr Allen, 2003; Locker, 1988). Therefore, it is not unexpected that individuals with similar clinical findings may experience different impacts on their quality of life.

4.1. Inflammation, Pain, and Perceptual Mechanisms

A linear relationship does not always exist between the clinical severity of periodontal inflammation and the symptoms perceived by individuals. Even when the inflammatory burden in gingival tissues is high, some individuals may report minimal pain or discomfort, whereas patients with relatively mild clinical findings may perceive pronounced symptoms. This phenomenon has been associated with variations in individual pain thresholds, peripheral and central perceptual mechanisms, and the heterogeneity of neuroinflammatory responses.(João Botelho et al., 2020; McGrath & Bedi, 2004; Pawar, Puranik, & Shanbhag, 2022).

4.2. Psychological and Social Determinants

Psychological status and social factors play a decisive role in shaping the perceived burden of periodontal diseases. The presence of anxiety, stress, and depressive tendencies may amplify the impact of periodontal symptoms on quality of life. In addition, aesthetic concerns and feelings of discomfort during social interactions may negatively influence OHRQoL scores, even independently of the severity of clinical findings.(Haag et al., 2017; Ng & Leung, 2006). This situation also highlights the indirect effects of periodontal diseases on social identity and self-confidence.

4.3. Education, Awareness, and Level of Expectations

An individual's level of education and awareness regarding oral health are among the key factors shaping the relationship between clinical periodontal findings and patient perception. It has been reported that individuals with higher levels of knowledge may

perceive even minor clinical changes and report negative impacts on their quality of life, whereas individuals with lower awareness may demonstrate limited symptom perception despite the presence of advanced periodontal findings.(Armencia et al., 2023; Ergin et al., 2011). This situation indicates that the level of expectations and health literacy are important determinants in OHRQoL measurements.

4.4. Behavioral Factors and Self-Care Habits

Oral hygiene behaviors and self-care habits are important determinants of the discrepancy between periodontal clinical status and the way individuals perceive their disease. In individuals who maintain regular oral care, the control of clinical findings may positively influence quality of life. In contrast, irregular oral care habits may negatively affect quality of life through feelings of guilt, loss of control, and perceived inadequacy.(Featherstone, 2004; Mouradian et al., 2007). It has been suggested that, particularly among healthcare professionals, professional knowledge and the responsibility of serving as role models may influence how periodontal findings are perceived. (Sang E Park, R Bruce Donoff, & Fidencio Saldana, 2017).

4.5. The Need for Integrating Clinical and Patient-Centered Measurements

Considering these multidimensional interactions, it becomes evident that approaches based solely on clinical parameters may not fully reflect the true burden of periodontal diseases on individuals. While clinical indicators reveal the biological status of periodontal

tissues, patient-centered measures make visible the impact of the disease on daily life. Therefore, incorporating OHRQoL measurements alongside clinical parameters in periodontal diagnosis and treatment processes provides a more realistic and patient-centered framework for evaluation.(Oh & Yu, 2021; Preshaw, Minnery, et al., 2024; Tonetti et al., 2025).

5. THE ROLE OF BEHAVIOR, EDUCATION, AND PROFESSIONAL IDENTITY

In the development, progression, and control of periodontal diseases, behavioral determinants play a role that is as critical as biological factors. Oral hygiene practices, regular dental check-ups, and an individual's self-care habits are among the key factors shaping periodontal clinical outcomes. However, the sustainability of these behaviors is largely determined by an individual's level of education, awareness, and health-related attitudes.(Petersen, 2005; Watt, 2012).

5.1. Education Level and Oral Health Behaviors

An increase in educational level is associated with greater knowledge and awareness regarding oral health. The literature indicates that individuals with higher levels of education tend to maintain more regular oral hygiene practices, recognize periodontal symptoms at earlier stages, and sustain preventive behaviors more consistently.(Armfield, Slade, & Spencer, 2009; Qin et al., 2019). However, it has also been emphasized that increased knowledge does not always translate into ideal behaviors; particularly in groups

exposed to heavy academic and professional workloads, this relationship may weaken.

5.2.Self-Care and the Role Model Effect Among Health Professionals

Health professionals are widely regarded as role models in shaping health behaviors within society. Studies have shown that among individuals receiving dental education, increasing clinical experience is associated with greater periodontal awareness and improved self-care behaviors. In contrast, in disciplines where oral health education is limited, this level of awareness may decrease over time.(Al-Omiri, Al-Wahadni, & Saeed, 2006; Armencia et al., 2023; Polychronopoulou, Kawamura, & Athanasouli, 2002). Perceptions of professional identity may also influence an individual's sense of responsibility toward their own health; consequently, this factor may emerge as an indirect determinant in the control of periodontal clinical findings.

5.3. The Interaction Between Behavior, Perception, and Clinical Outcomes

Behavioral factors influence not only clinical periodontal parameters but also patient-centered outcomes. It has been reported that individuals who maintain regular oral hygiene practices tend to have lower OHIP-14 scores, whereas those with inadequate self-care behaviors may report poorer quality-of-life perceptions even when clinical findings are similar.(Haag et al., 2017; Machado et al., 2020). This situation suggests that behavioral components may act

as mediating factors in the divergence between clinical findings and subjective experiences.

5.4. Long-Term Effects of the Educational Process

Habits acquired during the educational process are known to shape oral health behaviors even after graduation. Educational programs supported by periodontal training have been reported to promote lasting behavioral changes in individuals, whereas curricula that allocate limited attention to oral health may increase periodontal risks in the long term.(S. E. Park, R. B. Donoff, & F. Saldana, 2017). These findings indicate that oral health education should be structured not only to transfer professional knowledge but also to promote behavioral transformation.

5.5. Clinical and Educational Implications

Current evidence suggests that education and behavioral change play a central role in the maintenance of periodontal health. The sustainability of improvements in clinical parameters largely depends on an individual's ability to maintain self-care behaviors over the long term. Therefore, in the management of periodontal diseases, behavioral and educational strategies should be considered integral components of treatment planning alongside biological therapeutic approaches.(Preshaw, Ramseier, et al., 2024; Mariano Sanz et al., 2020).

6. CLINICAL AND RESEARCH IMPLICATIONS

Clinical parameters traditionally used in the evaluation of periodontal diseases are indispensable measures for identifying

biological damage and the inflammatory burden within periodontal tissues. However, these parameters do not fully reflect the impact of the disease on an individual's daily life, psychological status, and social functioning. The evidence discussed in this chapter demonstrates that a structural dissociation exists between periodontal clinical indicators and patient-centered outcomes, and that the burden of periodontal disease is not solely biological but rather a multidimensional phenomenon.

This divergence between clinical findings and patient perception necessitates a reconsideration of how periodontal treatment success is defined. Improvements in clinical parameters indicate the biological effectiveness of periodontal therapy, whereas patient-centered measures reflect the true impact of treatment on an individual's quality of life. Therefore, the success of periodontal therapy should be evaluated not only through changes in probing depth or attachment levels, but also through improvements in pain, functional capacity, aesthetic perception, and psychosocial well-being.

The integration of patient-reported outcomes (PROs) into periodontal research has the potential to enhance the clinical relevance of scientific studies. The use of valid and reliable instruments such as OHIP-14 enables a more objective and comparable evaluation of the effects of periodontal treatments on patients. This approach encourages the adoption of more comprehensive outcome measures in clinical research that consider not only biological improvement but also patient-centered benefits.

Considering the influence of education, behavior, and professional identity on periodontal health, the importance of multidisciplinary and educational approaches in oral health care becomes increasingly evident. Strengthening oral health awareness during the educational training of health professionals is particularly critical, both for maintaining individual periodontal health and for generating indirect benefits for public health. In this regard, oral health education should be supported by structured programs aimed at promoting sustainable behavioral change.

Future periodontal research should increasingly adopt study designs that evaluate clinical periodontal parameters together with patient-centered outcomes. Furthermore, the use of advanced analytical models examining the mediating roles of behavioral determinants, educational level, and psychosocial factors in periodontal outcomes may contribute to a deeper understanding of periodontal diseases. Such a holistic perspective will facilitate the development of patient-centered and sustainable clinical practices in the diagnosis, treatment, and follow-up of periodontal diseases.

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CHAPTER 4

SUBPERIOSTAL IMPLANTS IN THE MANAGEMENT OF THE SEVERLY ATROPHIC JAW: CURRENT EVIDENCE AND FUTURE PERSPECTIVES

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INTRODUCTION

Alveolar bone resorption following tooth loss represents a well-documented biological process that may lead to substantial vertical and horizontal bone reduction, particularly in cases of long-term edentulism. Progressive thinning of the alveolar ridge, cortical plate resorption, and reduction in trabecular bone volume ultimately result in the development of a severely atrophic jaw morphology. (Araújo & Lindhe, 2005)

Such anatomical alterations impose significant biological and biomechanical limitations on implant-supported prosthetic rehabilitation and complicate treatment planning in advanced cases of alveolar bone deficiency. (Tan et al., 2012)

Various surgical strategies have been proposed for the management of severe jaw atrophy, including block bone grafting, guided bone regeneration (GBR), sinus floor elevation, distraction osteogenesis, zygomatic implants, and short implant concepts. (Kim & Kim, 2024)

Although these approaches can facilitate implant placement in compromised anatomical conditions, they often require advanced

surgical expertise, prolong overall treatment time, and may increase morbidity—particularly in elderly patients or individuals with systemic comorbidities.

Subperiosteal implants were originally introduced in the mid-20th century as a means of providing prosthetic support in severely atrophic jaws without the need for intraosseous anchorage. Unlike endosseous systems, these implants are not inserted into the bone; rather, they consist of a metallic framework positioned beneath the periosteum and resting directly on the cortical bone surface, with stabilization achieved through multiple fixation screws. (Goh et al., 2025)

However, early clinical applications were associated with high rates of infection, soft tissue complications, and framework misfit, leading to a progressive decline in their use following the widespread adoption of osseointegration-based endosseous implant systems. (Bodine et al., 1996)

In recent years, advancements in cone-beam computed tomography (CBCT), computer-aided design and manufacturing (CAD/CAM), and three-dimensional titanium printing technologies have facilitated the reintroduction of patient-specific subperiosteal implants. Contemporary manufacturing techniques allow for improved passive fit, reduction in surgical stages, and optimization of biomechanical load distribution, thereby enhancing the predictability of this treatment concept. (Gellrich et al., 2025)

This chapter provides a critical appraisal of subperiosteal implants in the management of severely atrophic jaws, addressing their

historical development, biological foundations, biomechanical characteristics, surgical protocols, clinical indications, associated complications, and current evidence base.

Historical Development and Evolution

The concept of the subperiosteal implant was first described in the 1940s by Gustav Dahl. The systems developed during this period were designed as an alternative rehabilitation strategy for patients with advanced mandibular atrophy who were unable to achieve adequate stability with conventional complete dentures. (Dahl, 1943)

Classical subperiosteal implants were placed using a two-stage surgical protocol. During the first stage, the bone surface was surgically exposed, and an impression of the alveolar contour was obtained. Based on this impression, a patient-specific metal framework—typically cast from a cobalt–chromium alloy—was fabricated in the laboratory. In the second surgical stage, the manufactured framework was positioned beneath the periosteum. (Bodine et al., 1996)

These systems were not inserted into the bone; instead, they rested directly on the cortical bone surface and provided prosthetic support through transmucosal abutment extensions. Subperiosteal implants gained particular popularity between the 1950s and 1960s, especially in cases of advanced mandibular atrophy. (Kurtzman & Schwartz, 1995)

Nevertheless, early clinical outcomes were characterized by relatively high complication rates. The primary causes of failure included inadequate passive fit of the framework to the bone surface,

manufacturing inaccuracies related to casting techniques, chronic infections, soft tissue dehiscence and exposure, framework fractures, and insufficient fixation. In addition, the limited understanding of biomechanical load distribution at that time hindered proper analysis of stress concentration within the cortical bone. (Goh et al., 2025)

In the late 1960s and early 1970s, the introduction of the concept of osseointegration by Brånemark established a new paradigm in implant dentistry. The scientifically documented long-term success of endosseous implant systems led to a marked decline in the clinical use of subperiosteal implants. During this period, subperiosteal implants were largely regarded in the literature as a failed concept and were progressively abandoned. (Albrektsson et al., 1986; Brånemark et al., 1977)

Over the past 15–20 years, advancements in dental imaging and manufacturing technologies have enabled a renewed evaluation of subperiosteal implants. The introduction of cone-beam computed tomography (CBCT), computer-aided design and computer-aided manufacturing (CAD/CAM) systems, and additive manufacturing techniques such as selective laser melting (SLM) has made it possible to perform three-dimensional digital segmentation of the bone surface, design patient-specific frameworks, and substantially improve passive fit. As a result, the traditional two-stage surgical protocol has largely been rendered unnecessary, allowing for a more streamlined and predictable treatment workflow. (Goh et al., 2025)

Contemporary subperiosteal implants are typically manufactured using three-dimensional printing technologies rather than

traditional casting techniques, most commonly from Ti-6Al-4V alloy. This additive manufacturing approach enhances both biocompatibility and mechanical strength while significantly improving design accuracy and structural precision. (Bodine et al., 1996)

Currently, subperiosteal implants are considered an alternative treatment option in carefully selected cases, particularly in patients with Cawood and Howell class V–VI atrophy, in individuals who are not candidates for bone grafting or decline augmentation procedures, and in elderly patients or those presenting with systemic risk factors. The renewed interest in this concept suggests that historical failures were largely attributable to technological limitations rather than inherent biological inadequacies. In the contemporary approach, the underlying paradigm is no longer based solely on classical osseointegration, but rather on controlled biomechanical stability combined with patient-specific design principles. (Cawood & Howell, 1988)

Biology and Pathophysiology of Severe Jaw Atrophy

- **Alveolar Bone Remodeling Following Tooth Loss**

The resorptive process that begins in the alveolar bone after tooth loss represents a biological response driven by the absence of functional mechanical loading. Alveolar bone is a tooth-dependent structure, both embryologically and biomechanically. Following extraction, the mechanical stimulation transmitted through the periodontal ligament is eliminated, resulting in a shift in the bone remodeling balance toward resorption. This loss of functional loading alters the equilibrium between bone formation and resorption, favoring osteoclastic activity

and leading to progressive reduction in alveolar bone volume. (Araújo & Lindhe, 2005)

Clinically, pronounced horizontal bone loss is typically observed within the first 6–12 months following tooth extraction, whereas vertical resorption progresses more gradually but continues over time. During this period, trabecular bone volume decreases, the cortical plates become thinner, and the morphology of the alveolar ridge progressively flattens. In cases of long-standing edentulism, alveolar bone resorption may advance to such an extent that the residual ridge becomes scarcely distinguishable from the underlying basal bone (Araújo & Lindhe, 2005; Schropp et al., 2003).

- **Advanced Atrophy in the Context of the Cawood and Howell Classification**

The classification system proposed by Cawood and Howell provides a clinically relevant framework for describing morphological changes in edentulous jaws. According to this system, Class V cases are characterized by a low and flattened residual ridge, whereas Class VI represents a severely resorbed and depressed ridge morphology. (Cawood & Howell, 1988)

At this advanced stage of atrophy, alveolar bone height is critically reduced. In the mandible, the proximity to the inferior alveolar nerve becomes a significant limitation, while in the maxilla, pronounced sinus pneumatization is commonly observed. Additionally, diminished soft tissue support further compromises prosthetic stability. Under these

morphological conditions, placement of conventional endosseous implants is often not feasible without prior augmentation procedures. (Cawood & Howell, 1988)

- **Cortical and Basal Bone Dynamics**

In cases of advanced atrophy, the alveolar bone undergoes substantial resorption, whereas the basal bone is generally preserved. Basal bone is characterized by a denser cortical structure, lower metabolic turnover, and relatively stable behavior under functional loading. These properties provide a biomechanically reliable support zone in severely atrophic jaws, making the preserved basal cortex a potential anchorage area in complex rehabilitative scenarios. (Misch, 2008)

The subperiosteal implant concept is based on utilizing the preserved basal cortical bone as an anchorage surface. Unlike the conventional implant model that relies on intraosseous osseointegration, this approach is founded on broad surface contact with the cortical bone combined with multiple screw fixation. Accordingly, stability is achieved not through penetration into the bone, but rather through surface adaptation and mechanical fixation.

- **Mechanical Load Deficiency and Wolff's Law**

According to Wolff's law, bone tissue adapts structurally to the mechanical loads imposed upon it. Following tooth loss, the elimination of occlusal load transmission results in decreased osteoblastic activity and a relative predominance of osteoclastic resorption, ultimately leading to a reduction in bone volume. This biological mechanism

constitutes the fundamental basis of alveolar bone resorption observed after tooth extraction. (Frost, 1994; Turner, 1998)

Implant rehabilitation serves not only to restore prosthetic stability but also to re-establish functional load transmission, thereby contributing to the maintenance of bone homeostasis. Although subperiosteal implants do not integrate directly within the alveolar bone, controlled load distribution through the basal cortical bone may partially restore functional stimulation. However, in cases of uneven load distribution, there is a potential risk of stress concentration and microtrauma within the cortical bone, which may compromise long-term stability.

- **Biological Interface: Osseointegration or Fibro-Osseous Adaptation?**

In endosseous implant systems, clinical success is primarily defined by direct bone–implant contact, namely osseointegration. In contrast, subperiosteal implants do not penetrate the bone, and therefore the biological interface follows a different dynamic.

Two principal perspectives have emerged in the contemporary literature. The first suggests that limited surface bone adaptation may develop between the implant framework and the cortical bone. The second proposes that the formation of a stable fibrous capsule may be sufficient to achieve functional stability. The ongoing debate between these viewpoints represents a critical area of investigation in understanding the long-term biological performance of subperiosteal implants. (Albrektsson et al., 1986; Brånemark et al., 1977; Buser et al., 2017)

Design Principles and Manufacturing Technologies of Modern Subperiosteal Implants

- **Digital Planning and Patient-Specific Design**

The re-emergence of subperiosteal implants in contemporary clinical practice is largely attributable to advancements in digital imaging and manufacturing technologies. The planning workflow typically begins with high-resolution cone-beam computed tomography (CBCT), followed by bone segmentation and three-dimensional reconstruction based on the acquired data. This digital model is subsequently integrated with prosthetic planning according to the principles of prosthetically driven (reverse) planning, enabling the design of a patient-specific framework.

Through this approach, the implant framework is no longer mechanically adapted to the bone surface intraoperatively; instead, it is digitally designed according to the patient's existing bone morphology. This strategy significantly improves passive fit between the framework and the cortical bone, thereby reducing the adaptation-related complications historically associated with earlier designs. (Cerea & Dolcini, 2018; Gellrich et al., 2025; Joda & Gallucci, 2015; Revilla-León & Özcan, 2019)

- **CAD/CAM and Additive Manufacturing Technologies**

Contemporary subperiosteal implants are predominantly manufactured from Ti-6Al-4V alloy using additive manufacturing techniques such as selective laser melting (SLM) or electron beam melting (EBM). Compared with conventional casting methods, these

technologies provide superior dimensional accuracy and design precision.

The principal advantages of additive manufacturing include the ability to fabricate complex geometries, achieve homogeneous material structure, and optimize mechanical properties. In contrast, common limitations of traditional casting—such as metal shrinkage, misfit, and internal porosities—are largely eliminated.

This technological advancement represents a fundamental factor underlying the improved predictability of modern subperiosteal implant systems. (Lawrence et al., 2012; Traini et al., 2008)

- **Framework Geometry and Biomechanical Design**

Modern design principles focus on three primary objectives: homogenization of stress distribution, minimization of micromotion, and reduction of pressure on the overlying soft tissues. The geometry of the framework is therefore tailored according to both the underlying bone morphology and the anticipated prosthetic loading conditions.

In the mandible, the framework typically follows a horseshoe-like configuration aligned with the basal cortex. In the maxilla, a broader design encompassing the zygomatic buttress and anterior maxillary cortex is generally preferred. Screw placement is planned to achieve bicortical anchorage, with a symmetric distribution intended to mitigate stress concentration. In mandibular applications, the position of the inferior alveolar nerve constitutes a critical anatomical consideration during the design phase. At this stage, finite element analysis (FEA) serves as an important optimization tool for predicting the

biomechanical performance of both framework geometry and screw configuration. (Baggi et al., 2008; Natali et al., 2006; Shen et al., 2010)

- **Screw Fixation and Primary Stability**

In endosseous implant systems, primary stability is achieved through intraosseous placement and mechanical engagement within the bone. In contrast, primary stability in subperiosteal implants relies entirely on fixation screws. Consequently, screw-related parameters play a decisive role in the overall performance of the system.

Screw diameter and length must be selected in accordance with cortical bone thickness, as adequate cortical support constitutes the foundation of stability. Although increasing the number of screws may enhance load distribution, excessively rigid constructs can lead to localized stress concentration. Therefore, an optimal balance between sufficient stability and controlled elastic behavior must be established during the design process. Endosseöz implant sistemlerinde primer stabilite kemik içine yerleşim ve mekanik sıkışma ile sağlanırken, subperiostal implantlarda primer stabilite bütünüyle fiksasyon vidalarına bağlıdır. Bu nedenle vida parametreleri sistemin başarısında belirleyici rol oynar. (Meredith, 1998; Trisi et al., 2011)

- **Surface Characteristics: Porous versus Solid Designs**

The surface characteristics of the framework remain a subject of ongoing debate in the contemporary literature. Solid surface designs offer advantages such as improved hygiene control, reduced biofilm retention, and a comparatively lower risk of infection. In contrast, porous surface configurations may enhance superficial bone adaptation and provide mechanical interlocking at the bone–implant interface.

However, porous structures may complicate decontamination in the event of infection. Given the limited availability of long-term clinical data, no definitive superiority has been established between porous and solid designs. (Albrektsson & Wennerberg, 2004; Berglundh et al., 2018; Subramani et al., 2009)

- **Relationship Between Framework Design and Soft Tissue Management**

The success of subperiosteal implants depends not only on bone stability but also on the integrity of the surrounding soft tissues. During the design phase, mucosal penetration points should be minimized, prominent structures that may exert excessive pressure on the soft tissues should be avoided, and abutment positioning must be aligned with the prosthetic plan.

Considering that a substantial proportion of early failures are associated with soft tissue complications, it is evident that framework design must adhere not only to biomechanical principles but also to fundamental biological considerations. (Gellrich et al., 2025)

Biomechanical Principles and Load Distribution

- **Difference in Mechanical Paradigm**

In endosseous implant systems, load transfer occurs through the implant body into the alveolar bone, and clinical success is fundamentally dependent on direct bone–implant contact (osseointegration). Load distribution is predominantly axial in nature.

In contrast, subperiosteal implants do not involve intraosseous penetration. Instead, load transmission occurs along the cortical bone

surface, and primary stability relies entirely on screw fixation. Consequently, the biomechanical performance of the system is determined by framework geometry, extent of surface contact, and screw configuration. This approach is therefore based on controlled mechanical stability rather than biological anchorage through osseointegration. (Albrektsson et al., 1986; Brånemark et al., 1977; Buser et al., 2017)

- **Cortical Bone and Peri-Screw Stress Distribution**

In severely atrophic jaws, the preserved basal cortical bone serves as the primary load-bearing structure for subperiosteal implants. The high elastic modulus of cortical bone allows load to be distributed across broader surface areas; however, it also renders the tissue more susceptible to stress concentration.

Finite element analyses have demonstrated that peak stress values commonly occur at the screw entry sites. The number of screws and their symmetric distribution influence stress magnitudes, while bicortical fixation enhances overall stability. Screw diameter, length, and insertion angle represent critical parameters affecting long-term biomechanical performance. (Frost, 1994; Meredith, 1998; Trisi et al., 2011)

- **Framework Rigidity and Load Types**

The framework must possess sufficient rigidity to maintain structural stability; however, excessively rigid constructs may increase peri-screw stress and potentially contribute to cortical bone resorption. Conversely, overly flexible designs may permit micromotion, leading to loss of fixation and mechanical complications. Therefore, optimal

design requires a balanced mechanical performance that combines adequate stability with controlled elastic behavior.

Subperiosteal implants are particularly sensitive to lateral and torsional forces. For this reason, minimizing cantilever length and ensuring balanced occlusal loading are fundamental principles for achieving long-term biomechanical success. (Maló et al., 2015; Rangert et al., 1995)

- **Clinical Implications**

Current biomechanical evidence underscores the importance of framework designs with broad surface contact, multiple and symmetrically distributed fixation screws, and the integration of prosthetic planning into surgical design.

However, the correlation between finite element analysis findings and long-term clinical outcomes has not yet been fully established. This gap highlights that the biomechanics of subperiosteal implants remains an evolving field of investigation.

Surgical Protocol and Clinical Application

- **Preoperative Assessment**

Careful patient selection and comprehensive preoperative analysis are critical components in the planning of subperiosteal implants. Evaluation requires an integrated approach encompassing clinical, radiological, and systemic parameters.

During clinical examination, mucosal thickness, width of keratinized tissue, vestibular depth, and the presence of scar tissue should be meticulously assessed. Patients presenting with thin and

mobile mucosa are at increased risk of framework exposure. Previous surgical interventions and flap scarring may compromise soft tissue vascularity and wound closure capacity.

Radiological assessment necessitates high-resolution cone-beam computed tomography (CBCT). Particular attention should be directed toward basal cortical bone thickness, the position of the inferior alveolar nerve, the degree of maxillary sinus pneumatization, and the morphology of the zygomatic buttress. In this treatment concept, cortical bone quality and identification of appropriate screw fixation zones are more critical than overall bone volume.

Systemic evaluation should include assessment of glycemic control in diabetic patients, presence of osteoporosis, smoking status, and history of antiresorptive medication use. Given that subperiosteal implant placement involves extensive surgical exposure, the patient's wound-healing capacity constitutes an essential determinant in treatment planning.

- **Digital Planning Workflow**

The preoperative digital workflow begins with segmentation of CBCT data, followed by the generation of a three-dimensional bone model. Based on prosthetic requirements, a patient-specific framework is designed and screw insertion sites are defined accordingly.

During screw planning, bicortical engagement should be targeted, neurovascular structures must be preserved, and symmetric load distribution should be ensured. The prosthetically driven (reverse planning) approach allows the surgical design to be shaped according

to prosthetic demands and constitutes a fundamental principle for achieving biomechanical success.

- **Surgical Stages**

The surgical procedure is typically performed under general anesthesia or deep sedation. A wide mucoperiosteal flap is elevated to allow complete exposure of the bone surface. Flap design should enable tension-free primary closure. Preservation of periosteal integrity and maintenance of vascular supply are essential considerations.

The patient-specific framework is positioned onto the bone surface, and passive fit is carefully verified. Excessive force during adaptation must be avoided, as forced seating may increase peri-screw stress and predispose to subsequent mechanical complications.

Titanium fixation screws are placed at the predetermined sites to establish primary stability. Although bicortical fixation is generally preferred, the position of the inferior alveolar nerve must be meticulously evaluated in mandibular cases. Screw tightening should be controlled, as excessive torque may induce microdamage within the cortical bone.

Soft tissue management represents one of the most critical determinants of success in subperiosteal implant therapy. Tension-free primary closure must be achieved, and periosteal releasing incisions may be performed when necessary. Minimizing transmucosal abutment penetration reduces the risk of framework exposure. A significant proportion of early complications are related to soft tissue issues.

- **Postoperative Management**

In the postoperative period, antibiotic prophylaxis, anti-inflammatory therapy, recommendation of a soft diet, and meticulous oral hygiene instructions are essential. Sutures are typically removed within 10–14 days. Early postoperative swelling and hematoma formation may occur due to the extensive flap elevation required for the procedure.

- **Loading Protocols**

Because subperiosteal implants rely on mechanical fixation rather than intraosseous integration, they possess the potential for early loading. Nevertheless, screw stability, framework rigidity, and control of occlusal forces must be carefully evaluated. In clinical practice, a healing period of approximately 6–8 weeks is commonly preferred prior to definitive loading.

- **Clinical Challenges**

The principal complications associated with this system include soft tissue exposure, screw loosening, postoperative edema, and, rarely, framework fracture. Successful outcomes depend on the integrated execution of surgical technique, biomechanical design, and prosthetic planning.

Indications, Contraindications, and Patient Selection

- **Indications**

Modern subperiosteal implants should not be regarded as a substitute for routine implant therapy; rather, they should be considered

an alternative solution in carefully selected cases presenting with severe bone deficiency. This approach may offer a rational option particularly in clinical scenarios where augmentation procedures are associated with increased morbidity.

In cases characterized by critically reduced vertical bone height, diminished distance to the inferior alveolar nerve in the mandible, and pronounced sinus pneumatization in the maxilla, conventional endosseous implant placement often necessitates advanced surgical augmentation. In the presence of preserved basal cortical bone, subperiosteal implants may serve as an alternative rehabilitative strategy in such patients. (Cawood & Howell, 1988)

Resorption of block bone grafts, failure of guided bone regeneration (GBR), or complications following sinus floor elevation may result in repeated augmentation attempts that impose both biological and psychological burdens on the patient. In such circumstances, subperiosteal implants may be considered as a second-line treatment option. (Chiapasco et al., 2009; Esposito et al., 2009)

In elderly individuals, patients who are not suitable candidates for prolonged surgical procedures due to systemic conditions, or those unwilling to accept donor-site morbidity, subperiosteal implants may offer the potential for rehabilitation within a single surgical stage. However, this approach requires careful patient selection and thorough risk assessment. (Chiapasco et al., 2009; Esposito et al., 2009)

In selected cases presenting with segmental bone defects where vascularized bone grafting is not planned, patient-specific subperiosteal designs may serve as an adjunctive option. Nevertheless, this indication

should be limited to experienced centers and undertaken within a multidisciplinary treatment framework.

- **Contraindications**

Because subperiosteal implants require extensive surgical exposure and healthy soft tissue integrity, they are not recommended in certain clinical situations.

Implant placement is contraindicated in the presence of active infection, including periapical pathology, osteomyelitis, or uncontrolled periodontal disease. Similarly, thin and mobile mucosa, inadequate keratinized tissue, or extensive scar formation may increase the risk of framework exposure and should be considered relative contraindications.

Uncontrolled systemic conditions—particularly poorly controlled diabetes, significant immunosuppression, and severe tissue damage secondary to radiotherapy—may impair wound healing and increase the likelihood of complications. Furthermore, severe parafunctional habits, such as uncontrolled bruxism and excessive lateral loading, may intensify mechanical stress on the system and compromise long-term stability. (Chrcanovic et al., 2015; Monje et al., 2017; Ruggiero et al., 2022)

- **Decision-Making Algorithm for Patient Selection**

The indication for subperiosteal implant therapy should be evaluated based on three fundamental clinical questions:

1. Is the existing bone volume sufficient to allow placement of endosseous implants without augmentation?

2. Can the patient biologically and systemically tolerate augmentation surgery?
3. Does the basal cortical bone possess adequate thickness and quality to permit reliable screw fixation?

In situations where augmentation procedures are associated with high morbidity and the basal cortex is deemed sufficient, subperiosteal implants may represent a rational alternative. However, such decisions require a multidisciplinary approach integrating surgical, prosthetic, and biomechanical considerations.

Clinical Outcomes, Survival Rates, and Complications

Clinical outcomes of subperiosteal implants reported between the 1950s and 1970s were heterogeneous, with relatively high complication rates. Infection and framework exposure were frequently observed, and long-term survival rates demonstrated considerable variability.

However, these outcomes must be interpreted in the context of the period's technical limitations, including casting inaccuracies, framework misfit, limited biomechanical understanding, and inadequate soft tissue management. Therefore, historical failures appear to reflect technological and procedural constraints rather than inherent flaws of the concept itself. (Bodine et al., 1996; Goh et al., 2025)

In contrast, digitally designed and three-dimensionally printed systems introduced over the past 10–15 years have demonstrated more promising outcomes. Reported short- to medium-term survival rates

generally range between 85% and 95%. The most frequently observed complication is soft tissue exposure, whereas screw loosening is uncommon and framework fracture appears to be rare.

Nevertheless, the majority of available studies consist of case series, with follow-up periods typically limited to 2–5 years. Randomized controlled trials are currently lacking. Consequently, more robust evidence is required before definitive conclusions can be drawn regarding long-term success. (Cerea & Dolcini, 2018; Mommaerts, 2017)

Complications may be categorized as early (edema, infection, wound dehiscence), late (framework exposure, screw loosening, localized bone resorption), and mechanical complications (rarely framework or screw fracture). Long-term stability is largely dependent on soft tissue quality and appropriate biomechanical planning. Mechanical complications are most associated with excessive cantilever length, parafunctional habits, and asymmetric loading patterns. (Berglundh et al., 2018; Derks & Tomasi, 2015)

The complication profile of subperiosteal implants differs from that of advanced bone grafting procedures and zygomatic implants. In graft-based approaches, donor-site morbidity and graft resorption constitute primary concerns, whereas sinus-related and orbital complications are more prominent in zygomatic implant therapy. In contrast, soft tissue–related complications represent the most frequent challenges in subperiosteal implant systems. Accordingly, treatment selection should be based not only on reported survival rates but also

on the type and severity of potential complications. (Aparicio et al., 2014; Maló et al., 2015)

Current evidence indicates that subperiosteal implants are not intended to replace conventional implantology; rather, they may provide a rational alternative in carefully selected cases of severe jaw atrophy. Clinical success appears to depend largely on appropriate patient selection, meticulous soft tissue management, and sound biomechanical planning. (Esposito et al., 2009)

Comparison with Alternative Treatment Modalities

There is no universally accepted "gold standard" for the rehabilitation of severely atrophic jaws. Treatment selection varies according to residual bone volume, anatomical limitations, the patient's systemic condition, surgical tolerance, and the clinician's level of expertise.

In order to properly define the role of subperiosteal implants, a comparative analysis with currently available alternative treatment modalities is essential.

- **Bone Grafting and Augmentation Techniques**

Block bone grafts, guided bone regeneration (GBR), distraction osteogenesis, and sinus floor elevation are widely employed in cases of advanced bone loss. The principal advantage of these approaches lies in their ability to facilitate placement of endosseous implants, supported by robust long-term clinical data. Stability achieved through osseointegration constitutes the biological foundation of these techniques.

However, donor-site morbidity, risk of graft resorption, the need for multiple surgical stages, and prolonged treatment duration represent significant disadvantages. Subperiosteal implants may serve as an alternative by eliminating the requirement for grafting and potentially shortening overall treatment time. Nevertheless, the level of evidence supporting graft-based approaches remains superior. (Aparicio et al., 2014; Chrcanovic et al., 2016)

- **Zygomatic Implants**

Zygomatic implants represent an effective treatment option particularly in cases of advanced maxillary atrophy. Their ability to achieve high primary stability and, in many cases, allow immediate loading constitutes a significant advantage. Additionally, they may reduce or eliminate the need for bone grafting procedures.

However, the surgical technique is technically demanding and carries potential risks related to the maxillary sinus and orbital structures. For this reason, treatment is generally recommended in experienced centers. Long-term clinical data supporting zygomatic implants remain more robust compared with those available for subperiosteal systems. (Aparicio et al., 2014; Chrcanovic et al., 2015)

- **Short and Angulated Implant Concepts**

Short implants and angulated implant placement strategies, such as the All-on-4 concept, were developed to overcome posterior anatomical limitations. Their less invasive nature and extensive clinical experience constitute important advantages.

Nevertheless, these approaches require a minimum amount of residual bone volume and quality. In cases of severe atrophy where

adequate bone height or density is lacking, their applicability may be limited. Under such circumstances, subperiosteal implants may emerge as a potential alternative. (Felice et al., 2014; Maló et al., 2015)

- **Comparative Evaluation**

Overall, grafting procedures combined with endosseous implants are supported by strong long-term evidence, although they are associated with higher surgical morbidity. Zygomatic implants represent an effective solution particularly for maxillary atrophy but involve increased technical complexity and potential anatomical risks. Short and angulated implant concepts are less invasive; however, they may not always be applicable in cases of severe bone deficiency.

Subperiosteal implants offer the advantage of eliminating the need for grafting and utilizing the preserved basal cortical bone. Nevertheless, long-term clinical data remain limited, and successful implementation requires advanced digital planning and technical expertise. Accordingly, these systems should be regarded not as first-line therapy, but rather as an alternative option in carefully selected cases. (Goh et al., 2025)

- **Clinical Decision Perspective**

Subperiosteal implants may represent a rational option particularly in patients who are unable to tolerate augmentation procedures, present with critically reduced bone volume, and face elevated risks with alternative treatment modalities. However, considering the current level of evidence, there is insufficient long-term data to recommend these systems as a routine first-line therapy.

Treatment decisions should therefore be individualized, with biological, biomechanical, and surgical parameters evaluated in an integrated manner.

Future Perspectives and Research Directions

Although subperiosteal implants have re-emerged due to advancements in digital imaging and additive manufacturing technologies, the current literature indicates that this treatment concept remains in a developmental phase. Most published reports consist of case series with short- to medium-term follow-up, while long-term, prospective, and multicenter clinical data remain limited. Critical parameters—such as long-term bone stability, peri-screw bone resorption rates, structural integrity of the framework over time, and sustainability of soft tissue health—require more systematic investigation.

Furthermore, the biological nature of the bone–implant interface in subperiosteal systems has not yet been fully elucidated. The adaptation process may differ fundamentally from the classical osseointegration model, potentially introducing an alternative concept of implant–tissue integration within implant biology. Future research should therefore focus on histological characterization, thresholds of micromotion tolerance, and the long-term behavior of fibro-osseous responses.

From a design perspective, biomechanical optimization remains an evolving process. Hybrid frameworks incorporating selectively porous regions, micro-geometric modifications at cortical contact

zones, and refined screw configurations aimed at improving stress distribution warrant further exploration. The integration of artificial intelligence–assisted finite element analysis and automated design algorithms may enhance patient-specific biomechanical simulations, potentially increasing predictability and reducing complication rates.

Clinically, a significant proportion of reported complications are soft tissue related. Accordingly, future investigations should extend beyond bone stability to include parameters such as soft tissue thickness, width of keratinized mucosa, and biological compatibility of abutment design. The establishment of standardized success criteria and the conduction of high-level evidence clinical trials will be essential for defining the definitive role of subperiosteal implants in contemporary implantology.

Conclusion

Subperiosteal implants represent a contemporary reinterpretation of a historical concept, revitalized through advances in digital planning and additive manufacturing technologies. In carefully selected cases of severe jaw atrophy, they may offer a viable alternative for rehabilitation. Historical failures appear to have been largely attributable to technological and surgical limitations rather than intrinsic biological shortcomings of the concept. Modern design and manufacturing strategies have substantially improved predictability and biomechanical control.

Nevertheless, the current body of evidence does not support a paradigm shift in which subperiosteal implants replace conventional

implantology. Instead, they should be regarded as a specialized treatment option with defined indications, requiring meticulous patient selection and rigorous biomechanical planning.

Future high-level, long-term clinical investigations will be essential to definitively establish the role of subperiosteal implants within contemporary implant dentistry.

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CHAPTER 5

CURRENT APPROACHES IN AESTHETIC ZONE IMPLANT APPLICATIONS IN PERIODONTOLOGY

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INTRODUCTION

In contemporary dentistry, the discipline of implantology has evolved beyond the mere mechanical replacement of missing teeth into a multifaceted field where biology, aesthetics and technology converge. Achieving a successful therapeutic outcome particularly in cases involving the anterior region where aesthetic expectations are paramount requires not only surgical precision but also a profound understanding of the dynamics of the surrounding soft and hard tissues.

In modern implant surgery, the philosophy of "preserving tissue" has become significantly more critical than "reconstructing tissue". In this context, innovative techniques, the optimization of the peri-implant phenotype and strategic hard tissue augmentation have emerged as the primary determinants of long-term stability. Furthermore, the rapid transformation in digital dentistry has provided clinicians with highly predictable results by minimizing the margin of error from the initial planning phase through to final prosthetic rehabilitation.

This chapter, titled "Current Perspectives and Aesthetic Management in Implantology" aims to integrate the latest scientific evidence with clinical practice guidelines. Within this scope, we have addressed a wide spectrum of topics, ranging from the biological principles of peri-implant tissues and digital workflows to the management of aesthetic zone complications and contemporary surgical protocols. Our objective is to provide a guiding resource for both our academic colleagues and dental practitioners striving for aesthetic excellence in clinical practice.

Peri-implant Phenotype, Components, Similarities and Differences with Periodontal Phenotype

The periodontal phenotype is comprised of gingival thickness (GT), keratinised gingival width (KGW) and buccal bone thickness (BBT). In contrast, the peri-implant phenotype encompasses keratinised mucosal width (KMW), mucosal thickness (MT), supracrestal tissue height (STH) and peri-implant bone thickness (PIBT). It has been demonstrated that these components may exhibit variability between individuals and in different regions of the same individual (Avila-Ortiz et al., 2020).

The concept of phenotype encompasses not only genetic characteristics but also observable characteristics that interact with environmental factors. The 2017 World Workshop emphasised that the periodontal phenotype can vary depending on environmental and biological conditions (Jepsen et al., 2018). In clinical practice, the most commonly used parameter in defining periodontal phenotype is gingival

thickness. Gingival thickness is categorised as either a thin phenotype (less than 1 mm) or a thick phenotype (more than 1 mm). The thin periodontal phenotype is more prone to gingival recession in the presence of inflammation, while the thick phenotype is typically characterised by increased pocket depth (Tavelli et al., 2021; Bressan et al., 2011).

The concept of peri-implant phenotype has been defined as the morphological and dimensional characteristics of the soft and hard tissues surrounding the implant. Supracrestal tissue height is defined as the vertical dimension of the peri-implant soft tissue, extending from the mucosal margin to the bone crest. It has been documented that physiological bone resorption may occur during the healing process if the SDY is less than 3 mm. Consequently, a supracrestal tissue height of ≥3 mm is regarded as imperative for aesthetic and biological stability (Linkevicius et al., 2009; Berglundh et al., 1991).

From an aesthetic perspective, the absence of soft and hard tissue phenotypes, particularly in the anterior regions, can result in complications such as mucosal recession, abutment reflection, and colour changes (Bressan et al., 2011; Wang et al., 2021; Jung et al., 2007). Consequently, phenotype assessment is regarded as a pivotal component in the formulation of implant treatment plans.

In conclusion, although periodontal and peri-implant phenotypes have similar protective functions, their structural and biological differences require different risk profiles and treatment approaches. An accurate assessment of these differences is critical for the long-term success of the implant and the aesthetic outcomes.

Diagnosis, Treatment Planning and Risk Factors in Aesthetic Area Implant Applications

Dental implant procedures in the aesthetic region are complex treatment approaches that aim not only to provide functional rehabilitation but also to achieve aesthetic results that are similar to natural teeth. Consequently, the hard and soft tissue phenotype, individual patient factors, and surgical-prosthetic planning are of significant importance in implant treatment (Grunder et al., 2018).

Prior to undergoing implant treatment, it is imperative that patients undergo a comprehensive evaluation of their systemic health conditions. As demonstrated in the relevant literature, the success of implant treatment can be negatively impacted by unstable systemic diseases, the use of drugs affecting bone metabolism, smoking habits, and a history of radiotherapy or chemotherapy (American Academy of Periodontology, 2000; Diel et al., 2004; Zitzmann et al., 2008). While old age in itself does not represent a contraindication for implant treatment, the patient's systemic stability and compliance with treatment represent important criteria. However, in young individuals, ongoing craniofacial growth may pose risks, particularly in anterior maxillary implant applications (Op Heij et al., 2003). Furthermore, the presence of active periodontal infection and inadequate oral hygiene has been demonstrated to significantly increase the risk of implant failure.

The planning of implant treatment is predicated on clinical and radiological assessment. During this process, the existing periodontal condition, the prognosis of adjacent teeth, the volume of hard and soft

tissues, and anatomical boundaries must be carefully examined (Buser et al., 2004; Ramanauskaite & Sader., 2022; Tischler et al., 2004). Although panoramic and periapical radiographs are used as the initial diagnostic tools, cone beam computed tomography, a three-dimensional imaging method, allows for a more accurate assessment of bone volume and anatomical structures, particularly in the aesthetic area (Dula et al., 2001).

The peri-implant phenotype concept is comprised of four principal components: keratinised mucosal width, mucosal thickness, supracrestal tissue height, and peri-implant bone thickness (Avila-Ortiz et al., 2020; Jepsen et al., 2018). Individuals exhibiting a thin phenotype have been documented to demonstrate an elevated risk of mucosal recession and aesthetic complications. Conversely, ≥2 mm mucosal thickness and sufficient keratinised mucosa have been reported to have a positive effect on the stability of peri-implant tissues and the predictability of aesthetic outcomes (Lang & Löe et al., 1972; Mailoa et al., 2018; Suarez-Lopez Del Amo et al., 2016; Warrer et al., 1995).

The alterations in both hard and soft tissue following tooth loss have been demonstrated to directly impact the predictability of aesthetic success. As demonstrated in the research by Monje et al. (2023) and Schropp et al. (2003), traumatic tooth extractions, a history of periodontal disease, and thin buccal bone can increase alveolar ridge resorption. Consequently, the temporal arrangement of implant placement and the requisite bone and soft tissue augmentation procedures ought to be meticulously planned (Donos et al., 2021; Testori et al., 2018; Tonetti et al., 2017).

It is imperative to ascertain the optimal implant position in the aesthetic zone to ensure optimal papilla preservation and soft tissue stability. The extant literature recommends a minimum distance of 3 mm between two implants and a minimum distance of 1.5 mm between the implant and the natural tooth (Çakır & Karaca, 2015). Incorrect positioning of implants or insufficient tissue support can lead to aesthetic and functional complications in the long term (Chen et al., 2023).

The height of the papilla is contingent on the interproximal bone level. The ideal distance between the contact point and the bone crest is 3–5 mm. Preservation of interproximal tissue is imperative for the formation of papillae and the enhancement of the pink aesthetic score (Chow & Wang, 2010; Furhauser et al., 2005; Garabetyan et al., 2019; Salama et al., 1998).

As demonstrated in the relevant literature, the principal risk factors for implant failure and the development of peri-implant disease are as follows: history of periodontitis, smoking, insufficient bone quantity and quality, the region where the implant is placed, lack of primary stability, and prosthetic factors (Chrcanovic et al., 2017; Heitz-Mayfield et al., 2020). The precise evaluation of these risk factors is of paramount importance for ensuring long-term success of aesthetic region implant procedures.

Consequently, comprehensive diagnosis, individualised treatment planning, and careful management of risk factors in implant applications in the aesthetic region are fundamental determinants of both aesthetic and functional success.

Implant Placement Protocols for Single and Multiple Tooth Losses in Aesthetic Areas

The aesthetic zone is one of the anatomical areas where both functional and aesthetic expectations are highest in implant treatments. Although implant-supported restorations have been shown to offer superior long-term stability and patient satisfaction in comparison to traditional prosthetic approaches (Aghaloo et al., 2017; Singh et al., 2023), they require advanced planning due to their increased susceptibility to biological and aesthetic complications (Singh et al., 2023). In this region, the preservation of peri-implant hard and soft tissues, the correct three-dimensional positioning of the implant, and appropriate placement timing are among the key determinants of aesthetic success (El Askary et al., 2001).

During the preoperative planning phase, the following factors must be evaluated in detail: bone quantity and quality, soft tissue volume and biotype, lip position, smile line, and orthodontic requirements (El Askary et al., 2001; Kopp et al., 2003). Radiographic examinations, in particular cone beam computed tomography, have been identified as playing a critical role in the analysis of bone architecture (Kopp et al., 2003). In cases where bone volume is inadequate, socket grafting or advanced regenerative procedures should be incorporated into the treatment plan (Fradeani et al., 2004; Jananni et al., 2014).

Soft tissue biotype is a significant predictor of aesthetic success. As demonstrated in the relevant literature, individuals with a thin biotype have been shown to be more susceptible to gingival recession (Lee et al.,

2011; Evans & Chen, 2008; Cosyn et al., 2011). Conversely, patients with a thick biotype have been observed to exhibit more stable peri-implant tissues. It has been observed that peri-implant inflammation and marginal bone loss are more prevalent in cases where the amount of keratinised tissue is less than 2 mm (Schrott et al., 2009; Chung et al., 2006). The position of the lips and the smile line are fundamental factors in determining the aesthetic success of implant-supported fixed prosthetic treatments in the maxillary anterior region. This is particularly the case in patients exhibiting excessive gingival display, otherwise termed a 'gummy smile'. In such cases, the transition zone between the prosthesis margin and the soft tissue line is of critical aesthetic importance. Given that excessive gingival display can develop due to various aetiological factors, the literature describes various treatment approaches for this condition, including the application of botulinum toxin, soft tissue augmentation, orthodontics combined with orthognathic surgery, gingivectomy, osteotomy, apically positioned flap, and lip repositioning surgery. Consequently, treatment selection should be planned on an individual basis according to the patient's clinical condition and aesthetic expectations (See Jananni et al., 2014; Polo et al., 2008; Ihde et al., 2020; Simon et al., 2007).

The timing of implant surgery has become a critical planning element in modern implant dentistry, along with a better understanding of the dimensional changes that the alveolar bone undergoes after extraction. In contemporary practice, the strategy of implanting prostheses in regions that have undergone prolonged healing is now

widely disregarded. Instead, there has been an emphasis on protocols that facilitate reduction in treatment time and optimised management of tissue loss (Branemark et al., 1977; Brügger et al., 2015; Chappuis et al., 2013; Hämmerle et al., 2004). Consequently, the timing of implant placement is categorised as immediate, early, or delayed. The immediate implant placement procedure is carried out during the same session as tooth extraction, while the early implant placement procedure is performed after soft tissue healing (4–8 weeks) or after partial bone healing (12–16 weeks). It is only permissible to perform late implant placement subsequent to a minimum healing period of six months. The selection of the appropriate timing should be determined based on the alveolar bone condition and patient-specific clinical circumstances (Sites et al., 2009; Morton et al., 2014; Chen & Buser, 2008).

The immediate implant placement protocol is a selective procedure that can only be applied under ideal clinical conditions. This approach necessitates ≥1 mm thick sound facial bone walls, a thick gingival biotype, the absence of acute infection, and sufficient apical and palatal bone support to allow for three-dimensional accurate positioning of the implant ensuring adequate primary stability. However, it is important to note that such ideal conditions are seldom encountered, particularly in the anterior maxilla. Defects such as dehisence or fenestration of the facial bone are frequently observed (Januário et al., 2011; Braut et al., 2011; Chen & Darby, 2017). Although immediate implant placement without a flap is preferred in suitable cases because it reduces buccal gingival recession and lowers patient morbidity, it is a technically

challenging procedure requiring high surgical expertise due to the limited field of view and anatomical difficulties (Fürhauser et al., 2015).

Early implant placement with soft tissue healing (4–8 weeks) is a frequently preferred protocol in aesthetic areas, applied only after the post-extraction biological healing process has reached a certain level. During this process, spontaneous healing of soft tissues has been shown to improve surgical conditions by increasing the amount of keratinised mucosa and facial soft tissue thickness. In cases where the facial bone walls are thin or damaged, significant thickening of the mid-facial soft tissue has been shown to increase flap vascularity and healing capacity (Buser et al., 2017; Chappuis et al., 2015). Furthermore, the regression of infections in the extraction site, in conjunction with the initiation of apical bone formation, facilitates a more predictable and safe preparation of the implant site. It is evident that the early implant placement protocol with soft tissue healing is considered a reliable and predictable option in the aesthetic zone (Chen & Buser, 2008). This is due to the following biological advantages.

In cases where adequate primary stability cannot be achieved in the immediate or early period, particularly due to the presence of extensive periapical bone lesions, it is preferable to achieve only partial bone healing with early implant placement. The protocol facilitates the process of new bone formation in the apical region, thereby ensuring the implant is correctly positioned in three dimensions and securely fixed. Although rare in the anterior maxilla, it offers a clinically appropriate option for the rehabilitation of multi-rooted teeth.

The preference of patients for timely implant placement is well-documented (Smith et al., 2022), however, in certain cases, late placement may be necessary due to the healing period required (Jones et al., 2019). Indications for this approach include biologically young patients, pregnancy, postponement of surgery for systemic or personal reasons, extensive apical lesions, ankylosed teeth, and insufficient bone volume that does not allow for early implant placement. In such cases, the implementation of socket grafting is strongly recommended in order to reduce alveolar ridge loss (Morton et al., 2014).

The rehabilitation of a single tooth deficiency in the aesthetic zone necessitates the correct three-dimensional positioning of the implant due to elevated aesthetic expectations. The optimal implant position is determined by the necessity to minimise bone resorption, preserve the vascularisation of hard and soft tissues, and ensure an adequate distance from adjacent teeth (Testori et al., 2018). In the maxillary anterior region, it is recommended that the implant be placed 1.5–2 mm palatally relative to the incisal edge and with at least 2 mm of buccal bone thickness preserved (Grunder et al., 2005; Tarnow et al., 2000). It is imperative to maintain a minimum distance of 1.5 mm between the implant and adjacent tooth roots to ensure the preservation of proximal bone and papilla stability. In the apicocoronal direction, the positioning of the implant 3–4 mm apical to the gingival margin of the planned prosthetic restoration contributes to achieving biological width and soft tissue adaptation. Consequently, the utilisation of surgical stents constitutes a pivotal component in attaining the optimal three-dimensional positioning

of the implant. Correct positioning is a key factor in achieving long-term aesthetic and functional success (Choquet et al., 2001; Saadoun et al., 1999; Higginbottom & Wilson, 1996).

The rehabilitation of multiple tooth loss in the aesthetic region necessitates meticulous planning of the number of implants and their three-dimensional positioning. In this process, cone beam computed tomography is the primary tool for assessing the existing bone volume. In order to ensure both aesthetic and biological stability, it is recommended that an inter-implant distance of at least 3 mm and a tooth-implant distance of at least 1.5 mm be observed (Grunder et al., 2005). Owing to spatial constraints in the anterior maxilla, the placement of an implant for each tooth may not always be feasible. Consequently, case-based planning and the utilisation of computer-guided surgical stents are imperative. It is important to note that the utilisation of large-diameter implants may potentially augment the risk of soft tissue recession within the aesthetic zone. In cases of advanced hard and soft tissue loss, aesthetic rehabilitation may sometimes necessitate the use of artificial gingiva applications (Salama et al., 2009; Salama et al., 2010).

The success of treatment in terms of aesthetics is now widely accepted as one of the fundamental outcome criteria of treatment. Aesthetic indices developed in this context aim to evaluate not only the functional but also the visual and soft tissue adaptation of implant-supported restorations (Grunder et al., 2005; Testori et al., 2005; Belser et al., 2009). The Pink Aesthetic Score (PES) is a widely utilised metric in the evaluation of peri-implant soft tissues, with a foundation

encompassing seven parameters: papilla presence, soft tissue level, contour, colour, and texture.

The success of aesthetic outcomes in implant treatment is now widely acknowledged as a fundamental measure of treatment efficacy. Aesthetic indices developed in this context aim to evaluate not only the functionality but also the visual and soft tissue adaptation of implant-supported restorations (Grunder et al., 2005; Testori et al., 2005; Belser et al., 2009). The Pink Aesthetic Score (PES) is a widely utilised metric in the evaluation of peri-implant soft tissues, with a foundation encompassing seven parameters: the presence of the papilla, the level of the soft tissue, the contour, the colour, and the texture. The PES system facilitates objective evaluation of the aesthetic congruence between the soft tissue surrounding the implant and the natural dentition (Fürhauser et al., 2005).

Implant Selection and Ideal Positioning in the Aesthetic Area

The primary objective of dental implant treatment is twofold: firstly, to replace a lost tooth with a restoration, and secondly, to ensure long-term aesthetic and functional continuity. The success of implant treatment, particularly in the anterior aesthetic region, is contingent on various factors, including the amount of hard and soft tissue, gingival biotype, implant material, implant size, three-dimensional position of the implant, and loading protocols (Tonetti et al., 2019; Wood et al., 2004; Van der Weijden et al., 2009; Canellas et al., 2019).

Resorptive changes in the alveolar bone following tooth extraction render the timing of implant insertion a critical consideration. The protocols for implant placement are determined by the timing of implant application following tooth extraction, categorised as follows: (1) during or immediately after extraction (Type 1, immediate); (2) 4–8 weeks later (Type 2, early); (3) 12–16 weeks later (Type 3, delayed); and (4) ≥16 weeks later (Type 4, conventional) (Tonetti et al., 2019).

Immediate implant procedures have been shown to reduce the treatment period; however, they require meticulous case selection in terms of buccal bone stability and soft tissue level. In the immediate implant placement protocol, the stability of the buccal bone and the mid-facial mucosal level are critical for achieving aesthetic success. In order to facilitate the immediate application of implants in the anterior region, a minimum buccal bone thickness of >1 mm is required. In addition, the presence of a thick gingival biotype, the absence of acute infection, sufficient primary stability, and the presence of apical and palatal bone support to allow for correct three-dimensional positioning of the implant are also necessary. In instances where these conditions cannot be met, early implant placement should be favoured. In cases where primary stability cannot be predicted, the conventional implant placement protocol should be followed (Slagter et al., 2021; Buser et al., 2017). The implant loading protocols are divided into three groups based on the time between implant placement and attachment to the prosthesis: immediate (first week), early (1 week–2 months), and conventional (≥2 months) (Kan et al., 2018).

In the anterior region, the implant material and surface design are of critical importance due to the high aesthetic requirements of the procedure. Although pure titanium implants are still regarded as the gold standard due to their excellent mechanical properties and biocompatibility, they have disadvantages such as soft tissue discolouration, hypersensitivity, risk of peri-implantitis, and corrosion potential (Thoma et al., 2016; Padhye et al., 2023). Consequently, zirconium implants have been proposed as a substitute due to their aesthetic benefits (Tomasi & Derks, 2022). However, it has been documented that zirconium implants may exhibit higher rates of early failure in comparison to titanium (Remísio et al., 2023).

Narrow-diameter implants represent a significant treatment option in cases where bone volume is inadequate in the anterior region (Klein et al., 2014). categorised narrow-diameter implants into three categories and reported high success rates in appropriate indications. The documented success rates of these implants are notably high, particularly in cases characterised by reduced mesiodistal distance, narrow alveolar ridge, and limited interradicular space. However, it is imperative to note that sufficient buccal bone thickness is paramount for the optimal three-dimensional positioning of the implant. It has been observed that narrow-diameter implants may elevate the risk of peri-implant bone resorption when subjected to excessive loading (Onone Gialain et al., 2022).

Subsequent to tooth extraction, the alveolar bone undergoes resorption in both the vertical and horizontal directions. Consequently, it is recommended that treatment planning be conducted prior to extraction,

with spontaneous healing, immediate implant placement, or alveolar socket preservation options being evaluated. In the maxillary anterior region, the buccal bone layer frequently exhibits a thickness of less than 1 mm, thereby increasing the likelihood of substantial buccal resorption following extraction. The majority of resorption occurs within the first six months, with significant bone loss observed in both the vertical and horizontal dimensions during this period (Januário et al., 2011; Tan et al., 2012; Botticelli et al., 2004; Chen et al., 2007). Consequently, the utilisation of bone grafting and membranes may be recommended during immediate implant procedures.

While the success rate of implant-supported single crowns in the anterior maxilla is high, the aesthetic outcomes are not always predictable. The most prevalent complication in this region is soft tissue recession, which is predominantly associated with a thin tissue biotype, inadequate bone volume, and crestal bone loss. It is recommended that hard and soft tissue augmentation be performed during or prior to implant placement in order to ensure aesthetic and biological stability. Increased mucosal thickness (>2 mm) has been demonstrated to enhance the stability of the tissues surrounding the implant, thereby reducing the risk of midfacial recession and bone loss. The concomitant utilisation of connective tissue grafts is imperative in the prevention of aesthetic and functional complications, particularly in immediate implant applications (Stefanini et al., 2023; Thoma et al., 2021; Tsigarida et al., 2020).

The achievement of aesthetic success in immediate implant placement and loading is closely related to the following factors: the

experience of the clinician; the three-dimensional position and angle of the implant; the sagittal root position; the temporary restoration; and the abutment contour. Sagittal root position is a pivotal criterion in guiding case selection in implant placement planning, and is evaluated in four classes using cone beam computed tomography. In Class I, the root is adjacent to the labial cortical plate and thus constitutes the most suitable group for immediate implants and temporary restorations. In Class II, the root is located centrally within the alveolus, without any contact with the labial or palatal cortical plate. Such cases necessitate meticulous surgical planning. In Class III, the root is in close proximity to the palatal cortical plate, which may necessitate heightened surgical precision. In Class IV, the majority of the root is associated with both the labial and palatal cortical plates. These cases are contraindicated for immediate implant placement and necessitate prior hard and/or soft tissue augmentation. Furthermore, even minimal malposition of the implant in the buccal direction has the potential to result in aesthetic problems and soft tissue recession. It is imperative, therefore, to position the implant at least 1 mm palatally, based on the cervical margins of the adjacent teeth, in order to ensure aesthetic and biological stability (Kan et al., 2018; Fürhauser et al., 2022; Evans and Chen, 2008; Cosyn et al., 2012).

In conclusion, successful implant treatment in the aesthetic region requires a multidisciplinary approach. The selection of the correct implant, the timing of its insertion, the presence of sufficient hard and soft tissue support, and the ideal three-dimensional positioning are all key factors in achieving long-term biological and aesthetic success.

The Importance of the Amount of Peri-implant Keratinised Mucosa in Prognostic Success in Implantology

The long-term clinical success of dental implants is contingent not only on the processes of osseointegration and sufficient hard tissue volume, but also on the quantity and quality of the soft tissues surrounding the implant. In particular, the width of the peri-implant keratinised mucosa (KM) is considered an important prognostic factor in terms of implant stability, survival, peri-implant tissue health, and aesthetic outcomes (Tavelli et al., 2021; Lin et al., 2013).

The concept of 'peri-implant phenotype', developed concomitantly with the 'periodontal phenotype' defined at the 2017 World Congress, is defined as a three-dimensional tissue structure consisting of keratinised mucosa width, mucosal thickness, supracrestal tissue height, and peri-implant bone thickness (Jepsen et al., 2018; Avila-Ortiz et al., 2020). The peri-implant phenotype has been demonstrated to exhibit a robust correlation with peri-implant tissue health and implant stability.

It has been asserted that in circumstances where there is an absence of sufficient keratinised mucosa in the peri-implant region, effective management of dental plaque becomes challenging, resulting in the development of inflammation in the soft tissue. This condition can escalate from peri-implant mucositis to peri-implantitis (Monje and Blasi, 2019; Schwarz et al., 2018). In clinical and cross-sectional studies, greater plaque accumulation, bleeding on probing, and mucosal inflammation have been observed in implant areas with insufficient KM width (Grischke et al., 2019; Perussolo et al., 2018; Souza et al., 2016).

Moreover, an inadequate amount of KM has been documented to be associated with discomfort experienced by patients during the brushing process (Grischke et al., 2019; Roccuzzo et al., 2016).

Despite the absence of a consensus in the literature regarding the minimum keratinised mucosa (KM) width required to maintain peri-implant tissue health, there is strong evidence that the presence of ≥2 mm KM is clinically protective (Avila-Ortiz et al., 2020; Ramanauskaite et al., 2022; Warrer et al., 1995). Long-term follow-up studies have demonstrated that, even with adequate plaque control, the risk of soft tissue recession increases in implant areas with insufficient keratinised mucosa (Ramanauskaite et al., 2022). In experimental animal studies, it has been reported that in implant areas where keratinised mucosa is absent, susceptibility to dental plaque-induced tissue destruction increases, and both soft and hard tissues are adversely affected (Warrer et al., 1995).

When evaluating the effects of soft tissue biotype on hard tissue, it is noted that implants with a thick mucosal biotype exhibit less marginal bone loss and better peri-implant bone stability (Mailoa et al., 2018; Suarez-Lopez Del Amo et al., 2016). Insufficient supracrestal tissue height has been demonstrated to create a suitable environment for bacterial colonisation, thereby increasing the risk of marginal bone loss and peri-implantitis (Monje et al., 2023). Consequently, when evaluating the peri-implant soft tissue phenotype, it is imperative to consider not only the width of the gingival margin but also the mucosal thickness and vertical tissue dimensions (Lin et al., 2013; Monje et al., 2023).

It has been reported that increasing the amount of soft tissue through soft tissue augmentation procedures (free gingival graft, connective tissue graft, collagen matrices and dermal matrices) facilitates plaque control, reduces inflammation, and, in some studies, ensures more stable marginal bone levels (Thoma et al., 2018; Basegmez et al., 2012). Free gingival grafting has been shown to be more successful in terms of keratinised tissue gain compared to vestibuloplasty and alternative biomaterials (Basegmez et al., 2013; Roccuzzo et al., 2014).

In studies conducted in the aesthetic region, it has been reported that soft tissue grafting applied to implants significantly increased pink aesthetic scores and more effectively controlled peri-implant recession (Yoshino et al., 2014; Migliorati et al., 2015; Grunder et al., 2011). The application of connective tissue grafts following immediate implantation has been documented as a method to enhance aesthetic outcomes by preserving facial tissue volume (Cosyn et al., 2013; Grunder et al., 2011).

In conclusion, peri-implant soft tissue management is an important but often overlooked factor affecting implant success. As indicated by the extant literature, a keratinised mucosa width of at least 2 mm is conducive to the preservation of peri-implant tissue health and plays a role in the prevention of peri-implant diseases (Avila-Ortiz et al., 2020; Grunder et al., 2011). However, further long-term clinical and experimental studies are required to elucidate the interaction between KM width, mucosal thickness, bone morphotype, and patient factors.

Digital Implantation in the Aesthetic Area and Its Clinical Advantages

The implementation of dental implants in aesthetic regions poses considerable challenges for clinicians, attributable to elevated aesthetic expectations, constrained anatomical space, and the imperative to rehabilitate peri-implant hard and soft tissues in congruence with natural teeth. The achievement of optimal aesthetic and functional outcomes is contingent upon the three-dimensional positioning of the implant. Correct implant positioning is critical for long-term hard and soft tissue stability, optimal occlusion, balanced load distribution, and adequate oral hygiene (Testori et al., 2018; Saini et al., 2024; Buser et al., 2011; Tahmaseb et al., 2014).

Recent advancements in digital dentistry have led to significant improvements in the accuracy, predictability, and patient comfort of implant surgery and prosthetic treatments. Digital implantology is defined as a comprehensive treatment approach that encompasses data collection, virtual patient creation, computer-assisted surgical planning, guided implant placement, and CAD/CAM-based restoration production (Spagnuolo & Sorrentino, 2020; D'haese et al., 2017; Wang et al., 2024).

Consequently, cone beam computed tomography (CBCT) has become a fundamental component of digital implantology, owing to its capacity to provide high-resolution three-dimensional imaging with minimal radiation exposure. The utilisation of CBCT data facilitates a comprehensive evaluation of implant parameters, including size, depth, angle, and distance from anatomical structures, prior to surgical

intervention. This approach serves to mitigate potential complications, such as nerve damage, root perforation, and sinus complications (Strauss et al., 2024; Happe et al., 2018; Geng et al., 2015).

Computer-assisted implant surgery (CAIS) can be categorised into two distinct groups: static and dynamic. In static CAIS, implants are placed in predetermined positions using surgical guides produced based on digital planning (Chackartchi et al., 2022; Todaro et al., 2023; Franchina et al., 2020). In dynamic CAIS, the drill and implant position can be tracked in real time during surgery using real-time navigation systems.

Guided surgery offers the advantage of minimally invasive surgery, particularly due to its ability to enable flapless approaches. This technique has been shown to reduce marginal bone loss by preserving periosteal blood supply, shorten surgical time, and significantly reduce postoperative complications such as pain, oedema, bleeding, and trismus (Mangano et al., 2018; Vercruyssen et al., 2014; Arisan et al., 2010; Hultin et al., 2012). Furthermore, tooth-guided surgical guides have been reported to provide higher accuracy compared to bone- or mucosa-guided guides (Geng et al., 2015; Tahmaseb et al., 2018; Smitkarn et al., 2019).

Conversely, dynamic navigation systems offer surgeons intraoperative flexibility by displaying the actual position of the burr in three dimensions on the screen and allowing for immediate corrections. The utilisation of these systems is particularly advantageous in cases characterised by limited mouth opening and in anatomically risky areas. However, these systems are associated with certain disadvantages,

including high cost, a learning curve, and stringent technical precision requirements (Franchina et al., 2020; Jorba-García et al., 2021; Chen et al., 2018; Da Silva Salomão et al., 2021).

Another significant development in digital implantology is the integration of artificial intelligence and robotic systems. As Altalhi et al. (2023), Macrì et al. (2024) and Kurt Bayrakdar et al. (2021) demonstrate, clinicians are provided with evidence-based support in the form of artificial intelligence algorithms for the analysis of CBCT images, the assessment of bone volume and the planning of implants. The utilisation of robot-assisted implant surgery has been demonstrated to reduce human error by enabling high-precision control of the implant's position, angle, and depth. The FDA-approved Yomi robotic system is an innovative example of this, increasing implant placement accuracy by providing real-time tactile feedback (Huynh and Mangui, 2024; Troccaz et al., 2019; Wiedemann, 2023; Neugarten, 2024; Bolding and Reebye, 2022).

A major benefit of digital implant placement in the aesthetic zone is that it facilitates prosthesis-guided implant planning. Initiating the treatment plan with the restoration process ensures that the implant is placed in an optimal position, both functionally and aesthetically. This approach is critical for achieving natural-looking peri-implant mucosa, facilitating papilla formation, and ensuring long-term aesthetic stability (Happe et al., 2018; Geng et al., 2015; Choi et al., 2022; Ramanauskaite & Sader, 2022; Kim et al., 2022).

Digital workflows also enable the objective assessment of soft tissue thickness, keratinised tissue width, and colour matching through

intraoral scanners, spectrophotometry, and three-dimensional analyses. These technologies have been shown to reduce subjectivity in aesthetic evaluations and ensure more reliable monitoring of treatment outcomes (Strauss et al., 2024; Couso-Queiruga et al., 2021; Lee et al., 2020).

Digital implantology also offers significant advantages in terms of patient-dentist communication. Digital smile design and three-dimensional simulations have been shown to facilitate patient visualisation of treatment outcomes, thereby enhancing patient satisfaction and treatment compliance (Kayssoun et al., 2020; Amornvit et al., 2020).

Digital implantation in the aesthetic region is a contemporary treatment modality that enhances implant placement accuracy, reduces surgical trauma, accelerates the healing process, and optimises aesthetic outcomes. The integration of artificial intelligence, robotic systems, and advanced digital planning tools has led to the prediction that digital implantology will become the standard approach in aesthetic implant treatments in the future (Macrì et al., 2024; Wu et al., 2019).

Loading Protocols for Aesthetic Area Implants and Gingival Contouring: The Effect of Abutment Selection on Hard and Soft Tissues

Aesthetic zone implant procedures are among the most challenging areas of implantology. This is due to high patient expectations and the functional-aesthetic sensitivity of the region. The anterior region (extending from canine to canine, and in some cases to the first premolar)

is located within the smile line and therefore requires both white aesthetics (natural tooth form and colour of the crown) and pink aesthetics (healthy and symmetrical appearance of peri-implant soft tissues) to be achieved (Alanazi et al., 2024; Ioannou et al., 2015). Consequently, the efficacy of aesthetic implant treatment is not confined to the process of osseointegration, but rather is contingent on the preservation or reconstruction of hard and soft tissue architecture (Han et al., 2018).

As demonstrated by Abd-Elrahman et al. (2020), the process of resorption that occurs in the buccal bone following tooth extraction can result in a reduction in peri-implant soft tissue support and papilla loss. As reported in the extant literature, the long-term aesthetic stability of the implant is contingent upon the presence of a minimum of 1.8–2.0 mm of vital bone surrounding it. Insufficient bone thickness may result in aesthetic complications, including an increased risk of buccal dehiscence and fenestration. The soft tissue phenotype exerts a direct influence on aesthetic outcomes. As demonstrated by Tavelli et al. (2021) and Kan et al. (2021), in cases of thin phenotype, gingival recession and grey reflection of the implant-abutment structure are more prevalent. Conversely, the marginal gingival level exhibits greater stability when thick peri-implant mucosa and sufficient keratinised tissue are present.

The soft tissue phenotype exerts a direct influence on aesthetic outcomes. While the marginal gingival level exhibits greater stability in the presence of substantial peri-implant mucosa and adequate keratinised tissue, gingival recession and grey reflection of the implant-abutment

structure are more prevalent in cases exhibiting thin-phenotype characteristics (Kan et al., 2011; Fu et al., 2011). Consequently, in suitable cases, connective tissue grafting or free gingival grafting is recommended for phenotype modification (Tavelli et al., 2021).

It is imperative that implant placement in the aesthetic zone be planned retrospectively from a prosthetic perspective. It is recommended that the implant-tooth distance be a minimum of 1.5–2 mm, and that the implant-to-implant distance be a minimum of 3 mm (Morales Schwarz et al., 2025). Insufficient distances can lead to interproximal bone loss and a reduction in papilla height, causing the formation of a 'black triangle' (Buser et al., 2004).

In restorations involving multiple units, the number and distribution of implants are of critical importance for the balanced transfer of biomechanical loads. Cantilever extensions should be limited as much as possible, as they can lead to increased stress in the implant neck region and marginal bone loss (Donmez et al., 2025; Freitas da Silva et al., 2018; Torrecillas-Martinez et al., 2014). Moreover, achieving passive fit in implant-supported fixed prostheses is a fundamental requirement for long-term success (Leblebicioglu Kurtulus et al., 2022).

The loading of implants is categorised into three distinct protocols: delayed (3–6 months), early (4–8 weeks), and immediate loading. This classification is determined by the timing of the loading of the implants in relation to the prosthesis (Pjetursson et al., 2004). Current systematic reviews and meta-analyses demonstrate that early and immediate loading

of implants with adequate primary stability yields survival rates that are comparable to those observed with delayed loading (Eini et al., 2022).

The immediate loading of single-tooth implants has been shown to be advantageous in terms of reducing treatment time and enabling early soft tissue shaping (Scacchi et al., 2000). However, for the immediate loading protocol to be successful, sufficient primary stability (>30 Ncm), non-traumatic surgery, and controlled occlusal contacts are required (Scacchi et al., 2000; Eini et al., 2022).

In the context of multi-unit restorations, it is imperative to meticulously plan immediate loading, and if deemed necessary, to splint implants to ensure balanced load distribution (Meng et al., 2021). Research has shown that there is typically no substantial discrepancy between immediate and delayed loading with respect to marginal bone loss, papilla height, and aesthetic scores (Tallarico et al., 2016; Crespi et al., 2011; Ickroth et al., 2024). However, research has indicated that the risk of midbuccal mucosal retraction may be slightly increased in implants subjected to immediate loading (Pigozzo et al., 2018).

It has been demonstrated that peri-implant soft tissues possess the capacity to be shaped under controlled pressure. This facilitates the creation of natural gingival contours, particularly through temporary restorations (Canullo et al., 2018). Standard healing caps have been shown to lack the capacity to adequately replicate the anatomical configuration of natural teeth due to their cylindrical structure (De Rouck et al., 2009). Consequently, the utilisation of customised temporary restorations is recommended.

Temporary crowns prevent tissue collapse by supporting the papilla and marginal gingival structure and creating a 'healing matrix' for the final restoration (Parpaiola et al., 2013; Macintosh & Sutherland, 2004). The extant literature reports that stepwise shaping with temporary restorations provides a stable and aesthetic peri-implant tissue architecture within a period of 4-6 weeks (Son and Jang, 2011; Spyropoulou et al., 2009; Qian et al., 2025). In patients exhibiting a thin soft tissue phenotype, prosthetic shaping alone may prove ineffective; in such cases, support through connective tissue grafting is recommended (Fu et al., 2018).

The material and design of the abutment are of pivotal significance with regard to the hard and soft tissues surrounding the implant. While titanium abutments offer superior mechanical strength, zirconium abutments are particularly advantageous in aesthetic cases involving thin peri-implant mucosa, due to their white colour (Halim et al., 2022; Linkevicius & Vaitelis, 2015). Research has indicated that zirconium abutments may result in reduced plaque accumulation and inflammatory response (Sampatanukul et al., 2018). However, it has been reported that both materials yield similar results in the presence of sufficient peri-implant mucosa thickness (Soliman et al., 2021). In addition, although the 'one abutment–one time' approach has been proposed as a means of increasing soft tissue stability, the evidence supporting this hypothesis remains inconclusive (Linkevicius & Vaitelis, 2015). The success of aesthetic zone implant treatments is contingent upon meticulous planning that incorporates the following elements: precise surgical timing, suitable

loading protocol, effective soft tissue management, and the judicious selection of abutments tailored to the specific characteristics of each case. When biological, aesthetic and biomechanical factors are considered in conjunction with one another in single and multiple-unit restorations, implant-supported restorations have been demonstrated to achieve a high level of success in terms of long-term tissue stability and patient satisfaction.

Complications and Treatments in Aesthetic Area Implants

The field of implantology in the aesthetic region is widely regarded as one of the most challenging areas of the discipline. This is due to the complexity of anatomical structures, the thinness of facial bone walls, and the high expectations of patients. Consequently, the efficacy of treatment in this domain is contingent not solely on implant stability, but also on the preservation of bone and soft tissue, peri-implant health, and the adaptation of the prosthetic design to the natural appearance of the teeth (Buser et al., 2017; Jung et al., 2018; Chappuis et al., 2013).

The increased utilisation of technologies such as digital imaging, Cad/Cam systems, intraoral scanners, and guided surgery in implantology has been demonstrated to result in enhanced success rates. However, the prevalence of biological, mechanical and aesthetic complications remains a significant concern, largely attributable to errors occurring during surgical and prosthetic procedures (Jung et al., 2018; Chappuis et al., 2013; Cosyn et al., 2012).

Insufficient bone volume has been identified as the primary surgical complication. In order to achieve a stable aesthetic result, it is essential that the facial bone wall is at least 2 mm thick (Qahash et al., 2008). In cases of insufficient bone volume, guided bone regeneration, augmentation techniques, and socket preservation approaches can be applied (Chappuis et al., 2015; Urban et al., 2019; Benic & Hämmerle, 2014; Tatakis et al., 2015; Misch et al., 2008). Although nerve and vessel damage is less prevalent, it can result in significant complications due to the anatomical structures in the anterior region. Consequently, planning with CBCT is particularly recommended (Greenstein & Cavallaro, 2014; Jacobs et al., 2010; Chan et al., 2018).

Improper positioning of the implant is considered to be one of the most critical complications. Mesiodistal, coronoapical, and orofacial malposition have been demonstrated to result in a multitude of adverse outcomes, ranging from papilla loss to buccal bone resorption (Tarnow et al., 2000; Jemt and Albrektsson, 2008; Esposito et al., 2012; Choquet et al., 2001; Heitz-Mayfield et al., 2013; Nevins et al., 2013). As asserted by Tatakis et al. (2015), the distance between implants and adjacent teeth should be a minimum of 1.5 mm, with a minimum separation of 3 mm between them. Moreover, from an aesthetic perspective, it is also important to place the implant neck approximately 3-4 mm apical to the gingival margin (Belser et al., 1996). Failure to adhere to these criteria may result in aesthetic issues such as gingival recession, disruption of the restorative emergence profile, and exposure of implant components (Chen et al., 2023; Cosyn et al., 2016; Romandini et al., 2021).

"Soft tissue problems constitute another group of complications frequently encountered in the esthetic zone. While a deficiency in keratinized gingiva increases the risk of peri-implant inflammation and disease, these areas can be augmented through free gingival or connective tissue grafts (Wennström & Derks, 2012; Thoma et al., 2015). Loss of papilla occurs as a result of both hard and soft tissue support loss, leading to significant esthetic concerns. In particular, the inter-implant distance and restorative design directly influence papillary form (Tatakis et al., 2015; Jung et al., 2008). Furthermore, in patients with a thin biotype, buccal soft tissue recession occurring over time may result in a gray metallic shadows; in such cases, the selection of zirconium abutments and the application of connective tissue grafts offer effective solutions (Jung et al., 2008).

"Mechanical and prosthetic complications are also significant factors that adversely affect implant success and esthetic outcomes. These include prosthetic fractures, screw loosening, abutment-related issues, and implant fractures (Urban et al., 2019; Pjetursson et al., 2018). Inappropriate torque application, excessive occlusal loading, parafunctional habits such as bruxism, and the selection of prosthetic materials play a role in the development of these complications. From an esthetic perspective, color mismatch, emergence profile discrepancies, and loss of papilla are the most frequently encountered problems (Buser et al., 2017; Qahash et al., 2008). In such cases, successful results can be achieved through digital prosthetic planning, customized abutment designs, and soft tissue conditioning techniques.

Implant success in the esthetic zone requires a multi-faceted evaluation. Success is attainable through an accurate analysis of anatomical conditions, the utilization of digital planning, meticulous management of soft and hard tissues, precise design of the prosthetic framework, and regular patient follow-up. Furthermore, it is anticipated that future AI-based planning software, bioengineering products, and personalized treatment protocols will further reduce complication rates.

In conclusion, it is emphasized that implant applications in the esthetic zone represent a treatment field requiring high precision, and complications can be largely prevented through accurate planning, the use of contemporary technologies, and a multidisciplinary approach. Consequently, both long-term functional success and results closely mimicking natural tooth esthetics can be achieved.

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CHAPTER 6

LASER APPLICATIONS IN RESTORATIVE DENTISTRY

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INTRODUCTION

The first laser system intended for medical applications was developed in 1960 by Theodore Maiman, enabling the clinical use of focused light beams and laying the foundation for modern laser medicine (Sachelarie et al., 2024). Owing to its high precision and controllability, as well as its potential to enhance patient comfort, laser technology began to gain significant momentum in dental clinical practice particularly from the 1990s onward (Sachelarie et al., 2024).

Laser light can interact with target tissues in four different ways depending on their optical properties (Meire & De Moor, 2007; De Moor & Delme, 2009):

1-Absorption of laser energy by the target: The amount of absorbed energy depends on factors such as tissue pigmentation, the presence of light-absorbing agents (chromophores), the wavelength of the laser used, and its emission mode. Light absorption may initiate various photochemical and photophysical processes, including photothermal effects (heat generation), fluorescence (light emission), photo-oxidation (photobleaching), and photodynamic reactions.

2-Transmission of laser energy through the target: This occurs when the laser energy is not absorbed by the target tissue and passes through it without producing a significant biological effect. Transmission is largely determined by the laser wavelength and the optical characteristics of the target tissue.

3-Reflection of the beam from the target surface: In this interaction, the laser beam is reflected from the surface, resulting in no direct effect on the target tissue.

4-Scattering: This refers to the dispersion of light in multiple directions within the target tissue, which reduces the concentration and intensity of laser energy at a specific focal point.

Although lasers have been investigated in dentistry for more than two decades, their widespread incorporation into routine clinical practice has accelerated with recent technological advancements (Dang & Rallan, 2013; Maheshwari et al., 2020).

In restorative dentistry, lasers have a broad range of applications, including:

1. Cavity preparation,
2. Laser surface conditioning (roughening),
3. Polymerization of restorative materials,
4. Management of dentin hypersensitivity,
5. Tooth bleaching procedures,

6. Diagnostic applications, and
7. Preventive interventions.

1. Cavity Preparation

In dental practice, the removal of hard tissues is primarily achieved through two main approaches (Peres et al., 2019). The first involves conventional rotary bur systems, which were introduced at low speeds nearly a century ago and were often associated with vibration-induced discomfort. Today, these systems can operate at speeds of up to 400,000 rpm, thereby reducing vibration and related discomfort; however, continuous water cooling is required to protect pulpal tissues from thermal damage (Holden, 2020). The second approach comprises more recent ablation techniques based on laser systems, such as erbium lasers (Holden, 2020).

Laser-assisted caries removal aligns with the principles of minimally invasive dentistry and is considered a more comfortable and safe alternative to traditional rotary instruments, often improving patient compliance (Kasakawa et al., 2022). Additionally, its potential to reduce pain and enhance the effectiveness of local anesthesia offers significant clinical advantages (Abdrabuh et al., 2023; Khalighi et al., 2021).

Evidence indicates that the Er:YAG (Erbium: Yttrium Aluminum Garnet) laser is capable of effectively and efficiently ablating dental hard tissues (Li et al., 2019). Because carious tissue

contains a higher water content than sound tissue (Ito et al., 2005), erbium lasers applied below the ablation threshold of healthy tissue can selectively remove demineralized and infected structures while preserving intact tooth structure. This selective ablation contributes to maintaining structural integrity and may reduce the need for more extensive restorative procedures.

In an in vitro study, Sun et al. (2015) reported favorable outcomes for laser-assisted cavity preparation in Class V lesions. Similarly, findings from a 12-month clinical study conducted by Galafassi et al. (2017) demonstrated that laser-assisted cavity preparation positively influenced the clinical performance of Class I composite restorations.

Conversely, Valério et al. (2016) reported that, particularly in proximal wall areas where cavity preparation is technically challenging, rotary instrumentation may be more effective for caries removal compared with laser techniques.

Compared with conventional bur preparation, laser-assisted cavity preparation has been reported to produce distinct micromorphological surface characteristics that may enhance bonding performance (Verma et al., 2015). Laser-treated surfaces are characterized by clearly exposed enamel prisms, widened dentinal tubules, and the absence of a smear layer (Kiryk et al., 2021; Freitas et al., 2007; Wang et al., 2020). These morphological alterations are thought to facilitate adhesive penetration and improve micromechanical retention.

The intrapulpal temperature increase associated with Er:YAG laser application has been reported to remain below 3°C, and water cooling systems can also be employed during use (Maheshwari et al., 2020). The pulpal response to Er:YAG laser irradiation is generally considered minimal and reversible (Galui et al., 2019).

2. Enamel and Dentin Surface Conditioning (Laser Etching)

The literature indicates that laser applications may enhance the adhesion of restorative materials to dentin (Wang et al., 2020; Wei et al., 2023). This effect is attributed to increased surface roughness and bonding area, as well as the removal of the smear layer following laser irradiation (Wang et al., 2020). In particular, the application of the Er:YAG laser under appropriate parameters has been shown to open dentinal tubules and improve resin–dentin bond strength (Kasakawa et al., 2022).

Enamel absorbs laser energy, resulting in an elevation of surface temperature that may induce the formation of microscopic retentive features (Hedge et al., 2018). This altered surface morphology can promote improved adhesion of composite resin to tooth structure. The treated enamel surface often exhibits characteristics comparable to those produced by conventional acid etching (Hedge et al., 2018).

In contrast, due to its higher organic content, dentin may undergo carbonization during laser surface treatment, potentially leading to structural alterations (Maheshwari et al., 2020). Localized melting areas may form on the dentinal surface, which can result in

partial or complete occlusion of dentinal tubules (Maheshwari et al., 2020).

Studies have reported that enamel and dentin surfaces conditioned with Er,Cr:YSGG (Erbium, Chromium: Yttrium Scandium Gallium Garnet) lasers present irregular microstructural patterns and are generally free of a smear layer (Verma et al., 2012).

The long-term success of the resin–dentin bonding interface can be compromised by acidogenic bacteria accumulating within the oral biofilm (Hashem, 2021). The antimicrobial properties of laser irradiation may therefore contribute positively to bonding performance and clinical outcomes (Pourhajibagher et al., 2024).

3. Polymerization of Composite Resin Restorative Materials

Light-emitting diodes (LEDs) have become the predominant light source in dental light-curing units due to their portability, high energy efficiency, and stable light output (Price et al.,2015) . LED systems emit light within a narrow wavelength range in the blue spectrum (420–495 nm), with peak emission values typically between 445 and 470 nm. These spectral characteristics are specifically designed to correspond to the absorption maximum of camphorquinone/amine (CQ-amine) photoinitiator systems, thereby facilitating effective photopolymerization (Rueggeberg et al., 2011, Jandt et al., 2013).

Camphorquinone, one of the principal photoinitiators used to initiate polymerization in composite resin restorative materials, exhibits its highest activity at approximately 480 nm^2. In addition, the

monochromatic wavelengths of the argon laser, particularly at 488 nm and 514 nm, have been reported to be effective in the polymerization of composite resin restorative materials (Knezevic et al., 2007).

4. Management of Dentin Hypersensitivity

Dentin hypersensitivity represents one of the most frequently encountered complaints in clinical dental practice. Lasers have been shown to be effective in its management, primarily due to their ability to alter dentinal hydraulic conductance and induce occlusion of dentinal tubules (Tanushri et al.,2015).

In a study comparing the desensitizing effects of the Er:YAG laser with those of a conventional desensitizing agent on exposed cervical dentin (Schwarz et al., 2002), laser-assisted treatment was found to be effective in reducing hypersensitivity. Moreover, the clinical improvement achieved with the Er:YAG laser was maintained for a longer duration compared with the conventional desensitizing system.

5. Bleaching

Tooth discoloration is among the most common reasons patients seek dental treatment (Awati et al., 2024). A variety of treatment modalities with differing levels of invasiveness have been proposed for the management of discolored teeth, including external bleaching, microabrasion, dental veneers, crowns, or combinations of these approaches (Abidia et al., 2017). According to the American Academy of Cosmetic Dentistry, approximately 90% of patients prefer bleaching

as their treatment of choice (Pinto et al., 2017), and this method is regarded as the most minimally invasive option (Di Giovanni et al., 2018).

Although high concentrations of hydrogen peroxide (H_2O_2) are commonly used in in-office bleaching procedures, prolonged application times and the need for additional sessions remain significant limitations. For this reason, activation of bleaching agents has been recommended to shorten treatment (Maran et al., 2018, Yusof et al., 2020). Comprehensive investigations have demonstrated that various energy sources—such as halogen lamps, plasma arc lamps, xenon–halogen light sources, and lasers—can be employed to activate bleaching agents (Yusof et al., 2020). Several laser systems have been evaluated for this purpose, with potassium titanyl phosphate (KTP) lasers reported to enhance free radical release and promote photochemical bleaching. This mechanism enables effective results within a single clinical session and in a shorter time compared with prolonged at-home bleaching regimens (Bennett et al., 20215, Fekrazad et al., 2017, Zhang et al., 2007).

Lasers may be utilized for both vital and non-vital tooth bleaching (Galui et al., 2019). Because tetracycline–calcium chelate complexes and bleaching gels absorb visible green light within the 525–540 nm wavelength range, both diode lasers and KTP (potassium titanyl phosphate) lasers can be used for this indication (Bennett et al., 2015).

Compared with other light-activated bleaching systems, KTP laser-assisted bleaching is particularly directed toward the degradation

of tetracycline molecules and the elimination of gray discolorations (Bennett et al., 2015). Photodynamic bleaching performed with a KTP laser has been reported to exert no significant adverse effects on oral soft tissues, dental pulp, or tooth structure (Shahabi et al., 2018). Furthermore, KTP laser-assisted photodynamic bleaching has been described as a safe and effective method for managing age-related dental sclerosis discolorations. When combined with hydrogen peroxide, this system uniquely activates the bleaching gel through photothermal, photochemical, and photocatalytic mechanisms (Bennett et al., 2015).

While conventional bleaching techniques have been associated with an approximate intrapulpal temperature increase of 1.5 °C (Michida et al., 2009), laser activation of bleaching agents may produce temperature elevations ranging from 2 to 8 °C with LED, diode, and KTP laser systems (De Moor et al., 2015). Considering that temperature increases exceeding the critical threshold of 5.5 °C may pose a risk to pulpal health (Mollica et al., 2010), evidence-based comparisons of the biological effects of different laser systems are essential.

6. Diagnostic Applications

The early and accurate detection of dental caries plays a crucial role in preventing more severe oral health complications, reducing socioeconomic burdens, and supporting the principles of minimally invasive dentistry. The literature suggests the use of argon and diode lasers for the detection of dental caries through laser fluorescence

(Verma et al., 2012), while diode lasers have also been proposed for assessing pulp vitality (Zhang et al., 2025).

In clinical practice, diode lasers operating at a wavelength of 655 nm (e.g., DIAGNOdent and DIAGNOdent Pen systems) are widely used for caries detection. These devices analyze the fluorescence emitted by laser-stimulated dental tissues, enabling the identification and quantification of carious lesions (El-Sharkawy et al., 2022).

The laser fluorescence method can detect early and hidden carious lesions with high accuracy without exposing patients to ionizing radiation and provides information regarding the location and extent of the lesion. However, due to the potential for false-positive findings, it is recommended as an adjunctive rather than a primary diagnostic tool (Chan et al., 2023).

7. Preventive Applications

Carbon dioxide (CO_2) lasers exhibit a high absorption coefficient for hydroxyapatite. Reviews in the literature indicate that CO_2 lasers are among the most extensively investigated systems with respect to their caries-preventive potential (Al-Maliky et al., 2020). From a mechanistic perspective, Zancopé et al. (2016) first reported that CO_2 laser irradiation induces morphological alterations on the enamel surface, including fusion and melting. Carbonate within the hydroxyapatite structure is unstable and represents a component susceptible to acid dissolution (Robinson et al., 2000, Bachra et al., 1965). Irradiation of demineralized human enamel with a CO_2 laser has

been shown to reduce carbonate content (da Silva Tagliaferro et al., 2009), resulting in increased surface microhardness without producing pronounced morphological changes. Similarly, it has been demonstrated that CO_2 lasers operating at specific wavelengths can modify enamel hydroxyapatite crystals, thereby decreasing the mineral's acid reactivity (Rodrigues et al., 2004). Another review reported that a CO_2 laser at a wavelength of 10,600 nm exerts an inhibitory effect on demineralized enamel and dentin (Luk et al., 2020).

Fluoride is well established as an effective agent in caries prevention, and silver diamine fluoride contributes to remineralization while exerting antibacterial effects (Zhang et al., 2023). However, the action of topical fluoride is generally limited to the superficial layers (Singh et al., 2023). Consequently, the combined use of laser irradiation and topical fluoride has been proposed as a promising strategy for enhancing remineralization and caries prevention (Schmidlin et al., 2007, Poosti et al., 2014, Souza-Gabriel et al., 2015). The adjunctive application of CO_2 laser irradiation with fluoride therapy has demonstrated superior preventive outcomes compared with either CO_2 laser or fluoride treatment alone. This combined approach may allow the achievement of effective caries prevention with lower energy densities and reduced fluoride concentrations, thereby enhancing patient safety (Rodrigues et al., 2004).

The Er:YAG laser, operating at a wavelength of 2940 nm, is strongly absorbed by water. Liu et al. (2006) reported that Er:YAG laser irradiation significantly inhibited enamel demineralization. Similarly,

Mei et al. (2014) investigated the combined use of Er:YAG laser and silver diamine fluoride and found that laser application following silver diamine fluoride treatment on dentin surfaces enhanced resistance to the cariogenic effects of biofilm. Xue et al. (2022) further demonstrated that the combined use of diode laser irradiation and silver diamine fluoride was effective in preventing enamel demineralization.

The interaction between laser radiation and target tissues is governed by several key parameters, including wavelength (nm), power density (W/cm²), and the temporal characteristics of energy delivery. Temporal parameters encompass continuous wave or pulsed emission modes, pulse frequency (Hz), and pulse duration. For pulsed lasers, it is often more practical to express the energy delivered per pulse in joules (1 J = 1 W/s) rather than referring solely to average output power. Energy density (J/cm²) and fluence (energy per unit area) are also critical variables. Additional factors related to the mode of energy delivery—such as contact versus non-contact application, focused versus defocused beams, and beam diameter—also influence clinical outcomes (De Moor et al., 2015).

Laser–tissue interaction ultimately depends on the intrinsic properties of the tissue, as incident light may be absorbed, scattered, reflected, or transmitted to adjacent structures (Moradas Estrada et al., 2016). Therefore, wavelength selection is of paramount importance in clinical applications. The lasers commonly used in restorative dentistry and their respective wavelengths are presented in Table 1.

Table 1: Lasers Used in Restorative Dentistry and Their Wavelengths

LASERS	WAVELENGTH
Argon lasers	488nm (blue), 496nm (blue/green) or 514nm (green)
He-Ne lasers	632nm
Diode lasers	810 nm-980 nm
CO_2 lasers	10.600 nm
Nd:YAG lasers	1064 nm
Er:YAG lasers	2940 nm
Er, Cr:YSGG	2780 nm
KTP lasers	532 nm
Femtosecond lasers	800–1064 nm

Argon Lasers

Argon lasers operate within the blue–green region of the visible light spectrum and deliver energy through a flexible optical fiber system (David et al., 2015). They demonstrate a high affinity for pigmented tissues and hemoglobin, which enables effective coagulation (Vitruk et al., 2016). For this reason, argon lasers are particularly useful in controlling hemorrhage by targeting bleeding vessels (Vitruk et al., 2016).

These lasers are not efficiently absorbed by dental hard tissues; therefore, no special protective measures for teeth are generally

required during surgical procedures (Hedge et al., 2018). In oral tissues, argon laser irradiation does not typically result in significant reflection, although some degree of scattering, absorption, and transmission may occur.

One of the notable characteristics of argon lasers is their ability to polymerize composite resins. The blue wavelength (488 nm) is primarily used for composite resin polymerization, whereas the green wavelength (approximately 510 nm) is preferred for soft tissue procedures (Sharma et al., 2019).

He–Ne Lasers

In helium–neon (He–Ne) laser systems, helium functions as a catalyst by stabilizing excited neon atoms at their elevated energy levels, while neon serves as the active lasing medium (Maheshwari et al., 2020). Energy transmission is achieved through an optical fiber delivery system, and the output power typically ranges between 0.5 and 50 mW (Wu et al., 2008).

Diode Lasers

Diode lasers are commonly employed in a variety of clinical procedures, including aesthetic gingival recontouring, soft tissue crown lengthening, exposure of impacted teeth covered by soft tissue, removal of inflamed or hyperplastic tissues, frenectomy procedures, and photostimulation of aphthous and herpetic lesions (Hilgers et al.,2004).

CO_2 Lasers

CO_2 lasers exhibit a high absorption coefficient for water, resulting in significant thermal energy generation within irradiated tissues and a consequent propensity for rapid surface carbonization (Maheshwari et al., 2020). The carbonized layer that forms following irradiation serves as a protective biological dressing and is generally not removed, as it may contribute to hemostasis and surface protection (Maheshwari et al., 2020). Considering that oral mucosal tissues contain more than 90% water, laser energy is absorbed to a considerable extent within these structures (George et al., 2009). Owing to this pronounced absorption profile, CO_2 lasers are characterized by a limited penetration depth of approximately 0.2–0.3 mm (Julian et al., 2011). These systems operate exclusively in a non-contact mode and, among the lasers employed in the oral cavity, are recognized for exhibiting one of the highest rates of soft tissue ablation (Maheshwari et al., 2020).

Nd: YAG Lasers (Neodymium: Yttrium–Aluminum–Garnet)

Nd:YAG lasers exhibit low absorption by hydroxyapatite and water. Consequently, laser energy can penetrate deeply through enamel and dentin, potentially leading to pulpal temperature elevation (David et al., 2015). These systems may be operated in either contact or non-contact modes (Julian et al., 2011), although contact mode is particularly recommended during tissue procedures. Nd:YAG lasers have a penetration depth of approximately 2–4 mm (Aoki et al., 2000).

Operating at a wavelength in the near-infrared region, Nd:YAG lasers are well absorbed by pigmented structures such as melanin and hemoglobin (Marcondes et al., 2009). They are also readily absorbed by titanium, amalgam, and base metals (Wigdor et al., 1995). Therefore, caution is required when using this laser in the presence of such dental materials (Wigdor et al., 1995).

Erbium Lasers

The erbium "family" of lasers includes two primary wavelengths: Er,Cr:YSGG (yttrium–scandium–gallium–garnet) and Er:YAG (yttrium–aluminum–garnet) systems. The light emitted by Er:YAG lasers lies within the infrared spectrum and is therefore invisible to the human eye (Laky et al., 2023). Similarly, Er,Cr:YSGG lasers operate within the infrared region of the electromagnetic spectrum (Laky et al., 2023).

Erbium lasers demonstrate a high affinity for both hydroxyapatite and water, making them particularly suitable for the treatment of dental hard tissues (Harashima et al., 2005). In addition to hard tissue applications, erbium lasers may also be used for soft tissue ablation, as oral soft tissues likewise contain a high percentage of water (Ishikawa et al., 2008).

Femtosecond Lasers

Femtosecond laser systems are widely utilized in micro- and nanoscale manufacturing applications, particularly due to their ability to achieve highly precise three-dimensional processing (Chen et al.,

2016). These ultra-short pulsed lasers, with pulse durations shorter than one nanosecond (1 femtosecond = 10^{-15} seconds), deliver energy to the target tissue within an extremely brief time interval (Chen et al., 2016).

This rapid energy transfer induces direct ionization and plasma formation within the tissue. The swift dissipation of the generated plasma facilitates energy removal from the interaction site, thereby minimizing heat transfer to surrounding tissues (Gamaly et al., 2002). This mechanism is referred to as "cold ablation" and enables submicron, even nanometer-level, precision (Gamaly et al., 2002). Owing to these characteristics, femtosecond lasers may represent a potentially advantageous alternative to other laser systems for dental preparation procedures.

Conclusion

Laser technology has evolved into a versatile and increasingly integral component of restorative dentistry. Owing to their diverse wavelengths, tissue affinities, and interaction mechanisms, different laser systems provide targeted clinical benefits across a wide spectrum of applications, including cavity preparation, surface conditioning, polymerization, hypersensitivity management, bleaching, diagnosis, and caries prevention. In many of these areas, laser-assisted approaches align closely with the principles of minimally invasive dentistry by enabling selective tissue removal, improved micromorphology, enhanced antimicrobial effects, and greater patient comfort.

Nevertheless, clinical outcomes are highly dependent on appropriate wavelength selection, energy parameters, and delivery mode, as laser–tissue interaction is governed by both physical properties and biological responses. Although substantial evidence supports the efficacy and safety of various laser systems, further long-term, evidence-based clinical studies are warranted to optimize protocols and clarify their comparative advantages over conventional techniques. When applied with proper knowledge and parameter control, lasers represent a scientifically grounded and promising adjunct—or, in selected cases, an alternative—to traditional restorative procedures.

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