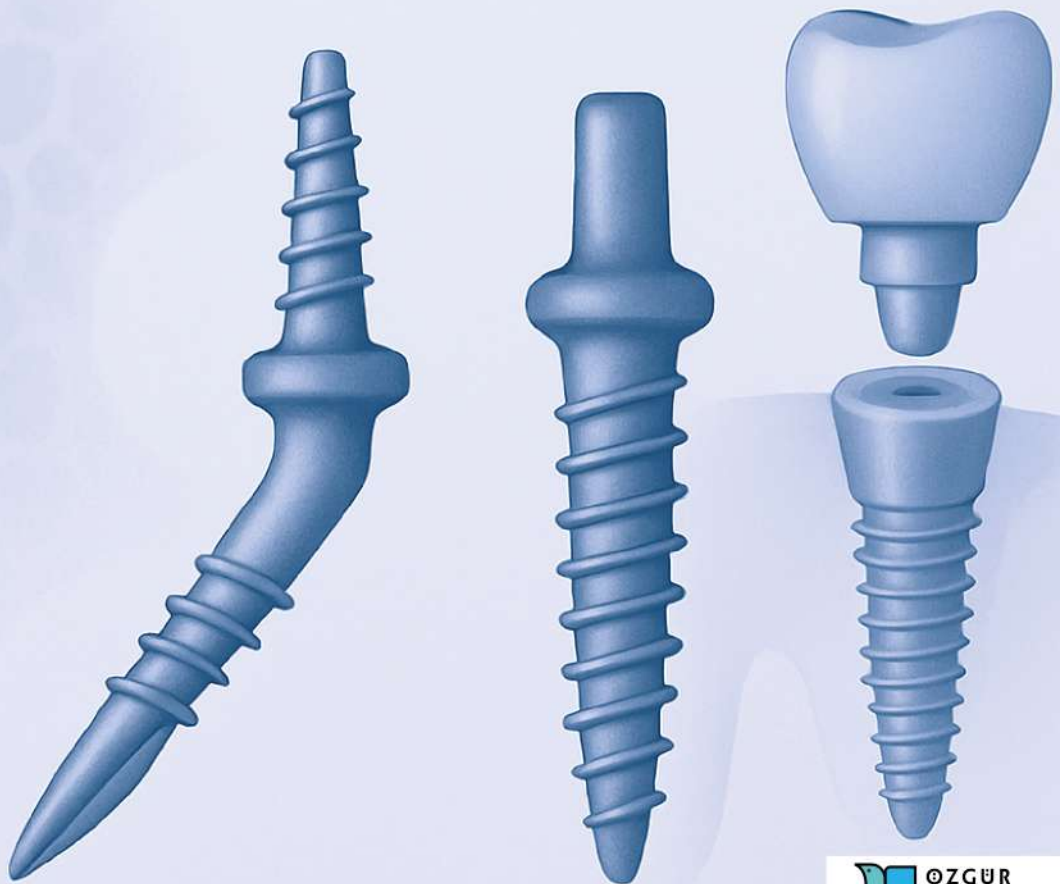


The Encoded Discipline in Bone:

From Orthodontic Anchorage to
Implant-Supported Rehabilitation

Editor: Asst. Prof. Dr. Gizem Yazdan ÖZEN



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Definition and History of Dental Implants

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Yerda Özkan Karasu⁴

Abstract

An implant is an artificial device placed in the body, typically expected to function in biological harmony with the body. These devices usually replace lost or damaged organs or tissues. The primary purpose of implants is to restore lost functions by replacing an organ or tissue, thereby regaining the system's functionality. Implants are widely used in various fields today.¹ They serve functions across a wide range, from dentistry to orthopedics, cosmetic surgery to neurological treatments.

1. Types of Implants

Dental Implants: The most common type of implant used in modern dentistry. Titanium screws are placed into the jawbone to treat tooth loss.² These implants, which fuse with the jawbone, offer aesthetic and functional solutions for many years.³

Orthopedic Implants: Implants used to treat bone or joint deformations.⁴ They are usually preferred in the healing of fractures or joint deteriorations.

Cosmetic Implants: Implants made to address aesthetic concerns include applications such as breast implants, rhinoplasty, and facelifts.

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Neurological Implants: Implants targeting the nervous system, such as the brain and spinal cord, are used to treat neurological diseases.⁵ Implants for treatment purposes are placed in Parkinson's, epilepsy, and spinal cord injuries.

Purpose of Implant Use:

The purpose of implant use is not limited to compensating for physical losses. It also aims to improve people's quality of life, correct functional disorders, relieve pain, and often achieve a more aesthetic appearance.

2. Development Process and Technological Advances of Implants

Developing Materials and Designs: The evolution of implant technologies has progressed in parallel with the development of materials used. The biocompatibility and durability of implant materials play a critical role in the success of treatment processes.

Use of Titanium: Until the mid-20th century, titanium was accepted as the first material compatible with bone. During this period, titanium attracted attention with its bone fusion capacity and became an ideal option for implants (Albrektsson et al., 1981).

Alternative Materials: Alternative materials such as zirconium have begun to be preferred, especially because they offer better aesthetic results.⁶ Zirconium is frequently used for dental implants because it has a more natural appearance than metallic color tones.⁷

Innovations in Bioengineering: In recent years, advances in bioengineering, especially with biotechnology and nanotechnology applications, have opened new horizons in implant design. Nanotechnology enables the microscopic improvement of implant surfaces.⁸ This enables faster bone integration and makes the implant more compatible with the body (Gallo et al., 2019).

3. Historical Development of Implants

Dental Implants in Ancient Times: Early Attempts:

The first dental implants date back to ancient civilizations.⁹ In Egypt, in the years 2000-3000 BC, artificial teeth made of gold, silver, or stone were found placed in the jawbones found in ancient tombs (Anderson, 2004). Seashells are also among the trials carved into the jawbone (Tunali, 2000). Although implants were not made with bone integration in the modern sense during this period, they were recorded as the first attempts to compensate for tooth loss. Archaeological findings show that there were similar applications

in Egyptian, Roman, and Chinese civilizations (Jones & Smith, 2010). In the ancient Mayan culture, people used dental prostheses made of stone or other hard materials to prevent tooth loss.¹⁰ These teeth were usually placed in the jawbone, but biological processes such as osseointegration were not used (Brown, 2015). In the 1930s, archaeological excavations in Honduras found a piece of jawbone with implants containing three pieces of shell carved into tooth shapes placed in the sockets of three missing lower incisors from the Mayan civilization. This is one of the oldest known examples of dental implants. Examinations also observed compact bone formation around two of them (SULLIVAN, 2001; Gaviria et al., 2014). In addition, initially, teeth were made from a wide variety of materials, such as ivory, bone, metals, and precious stones. It has also shown that early civilizations more than 2,000 years ago replaced missing teeth using carved stone, seashells, bones, and gold (Gaviria et al., 2014).¹¹

18th and 19th Centuries: First Scientific Approaches

In the Middle Ages, dental implantation was performed using allografts (tissues from the same species) and xenografts (tissues from different species). However, these practices did not become widespread due to the risk of infectious diseases and related deaths (Gaviria et al., 2014; Sullivan, 2001).

Late 1800s

Modern dental practice began to emerge in the 18th century. However, the scientific foundations of dental implants began to be laid at the end of the 19th century. During this period, dental prostheses generally consisted of removable dentures or metal frames attached to tooth roots (Williams, 1998).

1840s

In the 1840s, dentist Edward Maynard performed one of the first successful dental implants. Maynard used metal implants placed in the jawbone instead of tooth roots. However, these implants were generally not strong enough and had problems with biological compatibility (Green & Taylor, 2003). In the 19th century, in 1891, teeth made using porcelain and gutta-percha were implanted by Znamenski (1891) and Hillischer (1891). Payne (1902) applied the procedure by filling gold-plated tin capsules with gutta-percha, and Greenfield (1913) placed endosseous implants consisting of hollow caged iridio-platinum cylinders. A grooved disc with an artificial tooth attached to it was located at the top of each cylinder. The trepan used for the surgery had a cylindrical shape. A circular socket was prepared in the

jaw, leaving a core of bone on which the cylinder was placed. Greenfield hypothesized that the remaining core of bone in the implant site triggered the accumulation of new bone. The next 20 years did not see a major breakthrough in the field of implantology.

Early 20th Century

1930s

In the 1930s, the first attempts were made to use biocompatible metals such as titanium. However, the compatibility of implants with bone could not be achieved during this period, and success rates were low (Johnson, 2011).

1940s

The first titanium dental implants were made with the discovery of titanium metal, which would later become a very important material. However, the true potential of titanium implants was not understood until after the 1950s (Smith et al., 2017). It can be said that the history of modern dental implants began when Dr. Norman Goldberg, while in the army during World War II, began to try using metals used in other parts of the body in dental restorations. Later, in 1948, he and Dr. Aaron Gershkoff produced the first successful sub-periosteal implant (Gaviria et al., 2014). This laid the foundation of implant dentistry, as they pioneered the teaching of techniques in dental schools and dental associations around the world (Gaviria et al., 2014).

1950s, 1960s, and 1970s: First Clinical Applications and Development of Implant Design

One of the most important developments in dental implantology was the application of the first successful titanium dental implant to a patient by Swedish researcher Per-Ingvar Brånemark, who was an orthopedic surgeon (Gaviria et al., 2014). He placed implants in a 34-year-old human patient with missing teeth due to severe jaw and jaw deformities (Gaviria et al., 2014). Brånemark placed four titanium fixtures in the patient's mandible and, after a few months, used the fixtures as the basis for a fixed set of prosthetic teeth (Gaviria et al., 2014). This application later laid a foundation for the future use of titanium implants by achieving long-term successes (Brånemark, 1983). Brånemark's implants were the first dental implants to attach directly to the jawbone and remain stable for years.

Brånemark improved the design of implants, creating a safer and more effective system. Other researchers, inspired by Brånemark's findings,

developed their own implant systems, and titanium implants slowly began to spread in dentistry (Adell et al., 1981). Brånemark's method was based on the principle of "complete osseointegration." Brånemark conducted numerous studies on animals and humans.

Linkow's blade and Sandhaus's ceramic bone screw were introduced as a new concept in 1970 (Linkow and Cherchève, 1970). After 1970, efforts increased to understand and eliminate the factors that caused dental implants to succeed or fail.

1980s: Spread of Implants and Technical Developments

Following Brånemark's discovery, dental implants began to become more common. During this period, many studies were conducted on implant techniques, surgical procedures, and healing processes (Zarb & Schmitt, 1996). By the late 1980s, the success of implants exceeded 90%, and titanium implants began to be widely used worldwide (Albrektsson et al., 1986).

During this period, studies were conducted on the aesthetic properties of dental implants. Especially in the front teeth, the harmony of the implant with the gums and the appearance with the natural tooth was an important focus. The surface properties of implants, surgical methods, and healing processes were further developed during this period (Buser et al., 1988).

1990s: Surface Modifications and Advanced Technologies

Significant advances were made in implant materials and designs. During this period, the modification of implant surfaces became one of the most important strategies to increase osseointegration. Surface roughness allowed the implant to adhere better to the bone and increased the biological compatibility of the implant (Schwartz et al., 1998).

Macro and Micro Surface Structures: Surface modifications enabled better integration of the implant with the bone. Micro-rough surfaces facilitated the adhesion of osteoblast cells to the implant surface, accelerating osseointegration (Albrektsson, 1993).

Ion Coatings and Biological Applications: Ion coating technologies and surface improvements with biological molecules are important factors that increase implant success. During this period, the impact of biotechnology on implant treatment greatly increased (Coelho et al., 1999).

2000s and Beyond: Digitalization and Personalized Implants

The 2000s witnessed great advances in dental implantology with the widespread adoption of digital technologies. Computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies enabled more precise placement of implants (Misch, 2015). At the same time, three-dimensional imaging techniques (CBCT) allowed more detailed analysis of bone structure and personalized implant planning (Sümbül et al., 2020).

2010s: Surface Modifications and Innovations in Biomaterials

In the 2010s, implant surface modifications became an important research area. Hydrophilic surfaces provided faster healing at the bone-implant interface (Albrektsson & Wennerberg, 2019). At the same time, zirconia implants were developed as an alternative to titanium alloys, offering new options in terms of aesthetics and biocompatibility (Pjetursson et al., 2018).

2020 and Beyond: Personalized and Biotechnological Approaches

Today, artificial intelligence-supported planning systems optimize patient-specific implant designs. In addition, thanks to biomaterial research, biofunctional coatings that accelerate bone regeneration and patient-specific implants produced by 3D printing are becoming widespread (Chrcanovic et al., 2021).

Aesthetic and Functional Developments

Zirconium implants have begun to be preferred as an aesthetic alternative to titanium implants. Zirconium has the capacity to better mimic tooth color and does not have a metallic color tone. This feature is a significant advantage, especially for patients who want a more natural appearance (Gallucci et al., 2014).

Current Implant Studies and Experimental Approaches

Implant technologies have made significant progress, particularly in terms of biomaterials, surface coating techniques, and innovations that enhance osseointegration. Recent research focuses on increasing the longevity and biocompatibility of implants.

Next-Generation Biomaterials

Biomaterial research goes beyond titanium and its alloys, including new materials such as ceramics, polymers, and biocomposites. For example, hydroxyapatite coatings are an important biomaterial used to accelerate bone integration (Zhao et al., 2021). In addition, zirconia implants are increasingly preferred due to aesthetic concerns (Pjetursson et al., 2020).

Surface Modifications and Osseointegration

Surface modifications play a significant role in accelerating the osseointegration process. Techniques such as nano-level roughening, plasma spraying, and laser surface treatment enable bone cells to adhere better to the implant surface (Gittens et al., 2014). In particular, the addition of nanoparticles to the titanium surface increases the activity of bone cells (osteoblasts), providing faster healing (Luo et al., 2022).

Implants Produced with 3D Bioprinters

In recent years, 3D printing technology has revolutionized patient-specific implant design and production. Customizing titanium or bioceramic-based implants according to the patient's bone structure reduces failure rates (Schmidt et al., 2021). In addition, bone tissue engineering studies with bioprinting continue, which may pave the way for full biological implant production in the future.

Antibacterial and Smart Implants

Implant infections are a significant cause of failure. To overcome this problem, silver nanoparticle coatings are used to prevent bacterial colonization (Müller et al., 2023). In addition, some new studies aim to reduce the risk of infection by developing pH-sensitive implant coatings (Kumar et al., 2020).

Future Perspectives: Nanotechnology and Biomimetic Implants

In the future, dental implants will be developed with more biocompatible materials and more efficient healing processes. Nanotechnology will play a major role in improving implant surfaces and accelerating bone integration. In addition, biomimetic implants can provide higher success rates by mimicking the function and structure of natural teeth (Zhao et al., 2018).

Advanced Technologies

Today, advanced technologies in dental implants are being developed to shorten the osseointegration period, reduce the risk of infection, and increase the biological performance of the implant.

Historical Process

2000s: Cellular interactions were increased with nanotechnological surface modifications (Wennerberg & Albrektsson, 2009).

2010s: Laser technologies began to be used in precise surface modifications (Romero-Gavilán et al., 2015).

Today: Biomimetic approaches are used to make implant surfaces more biological by taking inspiration from nature (Hanawa, 2010).

Nanotechnology Applications

Nano-structured Coatings: Nano-sized hydroxyapatite or titanium dioxide coatings promote cell proliferation (Botticelli et al., 2011).

Nanotubes and Nanoparticles: Nanotubes applied to the titanium surface increase cell adhesion and strengthen the osteogenic cell response (Büttner et al., 2019).

Functional Nanoparticles: Silver or zinc oxide nanoparticles are used to impart antibacterial properties. These nanoparticles also provide controlled release of biomolecules that promote bone growth (Chrcanovic et al., 2017).

Laser Technologies

Femtosecond Lasers: Provides ultra-precise surface modification, creates microscopic roughness, and increases cellular interactions (Romero-Gavilán et al., 2015).

Laser Surface Hardening: Increases mechanical strength, improves wear resistance. Laser-created microchannels facilitate the adhesion of osteoblast cells to the implant surface.

Laser Surface Patterning: Used to create micro-patterns that promote cell adhesion. Laser-treated surfaces accelerate the healing process of tissues around the implant (Zhao et al., 2019).

Biomimetic Surface Modifications

Nature-Inspired Designs: Surface structures that mimic the bone matrix are developed. These structures allow cells to adhere better to the implant surface (Hanawa, 2010).

Hydrogel and Biopolymer Coatings: Creates cell-friendly, flexible surfaces. Biopolymer layers provide a stronger connection between bone tissue and the implant.

Biological Molecule Integration: Proteins and peptides that promote bone growth are attached to the surface, accelerating osseointegration.

Clinical Success Rates of Implants

The success of implant treatment depends on many factors. The main factors affecting the success rate include the patient's general health, the quality of the surgery, the quality of the implant, and the healing process.

Success Rates: Although the general success rate of implant treatment is over 90%, this rate may vary depending on the material used, the surgeon's experience, and the patient's health. In addition, personalized treatment plans should be created to increase the success rates of implants (Buser et al., 2017).

Complications and Early Failures: Although the failure rate of implants is generally low, complications can develop due to factors such as surgical error, infection, incorrect placement, or insufficient bone support. Therefore, appropriate patient selection and meticulous surgical techniques are required for successful implant treatment (Szalai et al., 2019).

Conclusion

Dental implants have made significant progress from scientific discoveries in the 1950s to the present and have revolutionized dentistry. The ability of titanium to integrate with bone has laid the foundation for implant treatment, and technological developments have made this treatment method more reliable, aesthetic, and functional. In the future, dental implants are expected to become even more perfect with biotechnological and digital advances. Dental implantology, which is an indispensable part of clinical dentistry today, is expected to reach 13 billion dollars in the global dental implant market in 2023. In addition, the survival rate of dental implants was reported to be over 90% (Lekholm, 1999).

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Dental Implant Procedures, Types, Materials, Surgical Procedures and Artificial Intelligence

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Abstract

Dental implants are considered one of the most reliable and effective methods for treating tooth loss. These structures, made from biocompatible materials such as titanium, are surgically placed into the jawbone to provide support for prosthetic teeth. Implant technology has advanced significantly since Brånemark's discovery of osseointegration in the 1960s, and today it has become even more successful thanks to digital planning, advanced biomaterials, and modern surgical techniques, all of which have improved precision and outcomes.

Basic Structure and Types of Dental Implants

Dental implants are classified into various types based on their placement location and design (Buser et al., 2017; Pjetursson et al., 2014).

1. Endosteal Implants

Endosteal implants are the most common type, placed directly into the jawbone. They are typically shaped like screws, cylinders, or blades. These

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implants have high success rates and are generally suitable for patients with good bone density (Misch, 2020). Made from titanium and titanium alloys to ensure biological compatibility with bone (Brånemark et al., 1977). Require high bone density and are produced in various diameters (Misch, 2020).

Screw Type: The most frequently used implant model, providing high stability. Most implant brands produce screw-shaped implants (Buser et al., 2017).

Cylindrical Type: Preferred in areas with lower bone density. These implants are often hydroxyapatite-coated (Bharadwaj et al., 2023).

Blade Type: Designed for use in narrow jawbones, though less commonly used today (Pjetursson et al., 2014).

2.Subperiosteal Implants

These implants are placed on top of the jawbone but under the gum tissue. They are particularly useful for patients with insufficient bone volume (Sivolella et al., 2018). Consist of metal frames that sit on the jawbone and integrate with the periosteum (bone membrane). Traditional subperiosteal implants are now being designed using 3D printers to match individual patient anatomy (Tafazal et al., 2021). Require a less invasive surgical procedure compared to endosteal implants (Moraschini et al., 2015).

3.Zygomatic Implants

These are long implants anchored to the cheekbone, used when there is insufficient upper jawbone (Chrcanovic & Albrektsson, 2020). Eliminate the need for sinus lifting and are a reliable option for patients with severe bone loss. Longer than traditional implants, they provide fixation to the zygomatic bone (Aparicio et al., 2021). Recent studies show that the 10-year success rate of zygomatic implants is over 95% (Chrcanovic et al., 2020).

4.Mini Implants

Smaller Diameter Implants: 2-3 mm in diameter, used in narrow spaces (Elsyad et al., 2019).

Temporary or Permanent Use: Can be used temporarily in orthodontic treatments or permanently to support prostheses (Moraschini et al., 2015).

Minimally Invasive Surgery: Their small diameter requires minimal surgical intervention (Bharadwaj et al., 2023).

Support for Removable Dentures: Effective in increasing the retention of dentures (Misch, 2020).

Short Recovery Period: Have a shorter recovery period than traditional implants (Pjetursson et al., 2014).

5. Stages of Dental Implant Placement

Clinical Evaluation and Planning: The success of dental implant placement depends on a careful clinical evaluation and planning process (Esposito et al., 2007).

Radiographic Examination: Panoramic X-rays and cone-beam computed tomography (CBCT) are used to assess jawbone volume and density. CBCT allows for three-dimensional examination of anatomical structures (Bornstein et al., 2014).

Patient's Medical History: Systemic factors such as diabetes, osteoporosis, and smoking can affect implant success (Chrcanovic et al., 2015).

Model Analysis: Intraoral scans and digital planning software are used to determine the optimal implant position (Joda & Brägger, 2018).

6. Surgical Stages

Anesthesia: Usually performed under local anesthesia; sedation or general anesthesia may be preferred in some cases (Kim et al., 2017).

Preparation of the Implant Bed: A suitable space is created in the jawbone using special drills.

Implant Placement: The titanium implant is carefully placed in a sterile environment.

Placement of the Healing Abutment: A healing abutment is placed on the implant to shape the soft tissue (Moraschini et al., 2015).

Healing Process (Osseointegration): The fusion of the implant with the bone, known as osseointegration, typically takes an average of 3 to 6 months. During this period, bone healing and implant stability are closely monitored to ensure successful integration. Recent advancements in surface coating technologies—such as bioactive surfaces and nanostructured coatings—have been developed to accelerate the osseointegration process and enhance implant success rates (Buser et al., 2017).

Prosthesis Application: After osseointegration is complete, an abutment is attached to the implant to serve as a connector between the **implant and the prosthesis**. A fixed or removable prosthetic restoration is then applied, depending on the patient's needs. Prostheses manufactured using CAD/CAM (computer-aided design/computer-aided manufacturing) technology offer enhanced precision and fit, contributing to improved functional and aesthetic outcomes (Zembic & Wismeijer, 2014).

The success of implant surgery is directly related to the patient's overall health and the suitability of the oral cavity (Esposito et al., 2007).

Medical Evaluation: The patient's systemic diseases (diabetes, osteoporosis, bleeding disorders) should be investigated.

Radiological Imaging: Bone volume and density are determined using panoramic radiography and CBCT (Bornstein et al., 2014).

Model Analysis and Digital Planning: Three-dimensional simulations are created using intraoral scans (Joda & Brägger, 2018).

Identification of Risk Factors: Factors affecting implant success, such as smoking and periodontal disease, should be evaluated (Chrcanovic et al., 2015).

7.Pre-Surgical Preparation

Sterilization and Antisepsis: The surgical area should be cleaned with antiseptic solutions to minimize the risk of infection.

Antibiotic Prophylaxis: Antibiotics may be administered before surgery to reduce the risk of infection (Lang et al., 2011).

Patient Education: The patient should be given detailed information about post-implant care.

Bleeding Control: The patient's coagulation status should be evaluated to prevent possible complications (Moraschini et al., 2015).

8.Stages of Implant Surgery

Determination of Anesthesia and Surgical Method

In implant surgery, determining the appropriate anesthesia method is essential for ensuring patient comfort and successfully completing the surgical procedure (Kim et al., 2017).

Local Anesthesia: In most implant surgeries, infiltration or regional block anesthesia is preferred (Haas, 2002).

Sedation or General Anesthesia: Can be applied, especially in complex cases and patients with high anxiety (Malamed, 2019).

Patient Comfort: Additional measures should be taken to ensure patient comfort during the procedure.

Anesthesia-Related Risks: Possible allergic reactions and complications to local or general anesthesia should be evaluated (Boynes et al., 2010).

Surgical Incision and Flap Methods

Incision and flap methods used in implant surgery directly affect the success of the surgery and the healing process (Buser et al., 2017).

Mucoperiosteal Flap: A standard incision method applied to expose the bone structure. This technique helps to correctly position the implant (Buser et al., 2017).

Flapless Technique: A minimally invasive approach that can accelerate the healing process, but requires careful planning (Cochran, 1999).

Infection Control: Keeping the surgical area sterile is critical to prevent postoperative complications (Lang et al., 2011).

Flap Closure Techniques: Appropriate closure methods should be determined depending on the surgical technique used.

Osteotomy and Preparation of the Implant Bed

Proper preparation of the implant bed is a fundamental factor affecting implant stability and the osseointegration process (Pjetursson et al., 2012).

Use of Drills: Bone tissue is gradually expanded to match the implant diameter.

Torque Control: A specific torque value should be applied when placing the implant to preserve bone integrity (Pjetursson et al., 2012).

Cooling Mechanism: Adequate cooling should be provided during osteotomy to prevent thermal necrosis (Eriksson & Albrektsson, 1983).

Bone Hardness Evaluation: Bone density should be evaluated in order to provide primary stability.

Implant Placement and Primary Stability

Correct positioning of the implant is a critical factor for long-term success (Mericske-Stern et al., 1996).

Implant Placement: Titanium or zirconium implants are screwed into the bone and fixed.

Primary Stability: Initial mechanical stability directly affects the osseointegration process (Moraschini et al., 2015).

Implant Angle Control: Placing the implant at the appropriate angle increases functional and aesthetic compatibility during the prosthetic phase (Joda & Brägger, 2018).

Attention to Anatomical Structures: Implant placement should be done by protecting nerve and vascular structures.

Healing Phase and Osseointegration

The osseointegration process is one of the most important stages determining the long-term success of the implant (Albrektsson & Johansson, 2001).

Closed Method: The implant is covered with tissue, and after healing is complete, it is opened with a second surgical procedure.

Open Method: The implant is placed with a healing abutment and comes into direct contact with the gum.

Healing Time: Usually varies between 3 and 6 months and may differ depending on implant surface properties (Buser et al., 2017).

Follow-up Examinations: Regular clinical and radiological checks should be performed to determine whether osseointegration is successful.

Advanced Surgical Techniques

In some cases, standard implant procedures cannot provide sufficient bone support. In such cases, advanced surgical techniques are applied to increase bone volume (Jensen & Terheyden, 2009).

Sinus Lifting

The sinus lifting procedure is applied in cases where bone height is insufficient in the maxillary posterior region (Wallace & Froum, 2003).

Lateral Window Technique: The traditional method preferred in cases of severely insufficient bone quantity (Boyne & James, 1980).

Transcrestal Technique: A less invasive alternative that can be applied in the limited bone deficiencies (Summers, 1994).

Use of Bone Graft: Volume can be increased by applying autogenous, allogeneic, xenogeneic, or synthetic graft to the sinus cavity (Del Fabbro et al., 2008).

Prevention of Complications: Careful surgical techniques should be applied to prevent risks such as sinus membrane perforation, infection, and graft resorption (Pjetursson et al., 2009).

Bone Grafting

Bone grafting techniques are applied to increase implant stability in patients with insufficient bone volume (Aghaloo & Moy, 2007).

Autogenous Grafts: Grafts taken from the patient's own bone, which have the highest osteogenic potential (Misch, 1999).

Allogeneic Grafts: Processed bone grafts obtained from human cadavers. May exhibit osteoinductive properties (Cordioli et al., 2001).

Xenogeneic Grafts: Animal-derived (usually bovine) bone grafts with a long resorption period (Jensen et al., 1996).

Synthetic Grafts: Hydroxyapatite and β -tricalcium phosphate-based grafts produced from biocompatible materials (LeGeros, 2002).

9. Dental Implant Materials

The biocompatibility, durability, and longevity of implants depend on the materials used (Cochran, 1999).

Titanium and Alloys

Biocompatibility: Titanium is a metal with high compatibility with human tissue (Brånemark et al., 1969).

Osseointegration: Has the property of direct fusion with bone (Albrektsson & Johansson, 2001).

Corrosion Resistance: Resistant to fluids in the oral environment (Geetha et al., 2009).

Alloy Options: Different types are available, such as pure titanium (Grade 1-4) and titanium alloys (Ti-6Al-4V) (Sidhu et al., 2016).

Mechanical Durability: Provides high strength in long term usage.

Zirconium Implants

Metal-Free Structure: White-colored implants that meet aesthetic requirements (Manzano et al., 2014).

Less Plaque Accumulation: May reduce biofilm adhesion compared to traditional titanium implants (Depprich et al., 2008).

More Brittle Structure: Mechanical strength is not as high as titanium (Piconi & Maccauro, 1999).

Better Soft Tissue Compatibility: Provides better aesthetic compatibility with gums.

Radiopaque Property: Clearly visible in radiographic imaging.

Ceramic and Polymer Implants

Biocompatible Ceramics: Hydroxyapatite-coated implants enhance bone compatibility (LeGeros, 2002).

Polymer Materials: Still in the experimental phase and being researched to improve bone compatibility (Bauer et al., 2017).

Composite Materials: Titanium and ceramic combinations are used to improve implant surface properties.

Future Potential: Next-generation polymer implants are being developed with biomaterial engineering.

Mechanical Durability: May have lower strength than traditional materials.

10. Surface Treatment Technologies

Plasma Spray Coating: Enhances bone adhesion by applying hydroxyapatite to the titanium surface (De Groot et al., 1987).

Acid Etching: A method that supports osseointegration by roughening the implant surface (Buser et al., 1991).

Sandblasting Technique: Enables mechanical processing of the surface.

Nanotechnology Applications: Surface modifications have been developed to reduce bacterial adhesion and increase tissue compatibility (Chouirfa et al., 2019).

Laser Surface Treatment: Optimizes the implant surface at a microscopic level (Gittens et al., 2011).

11. 3D Printers and Dental Implant Production

In recent years, 3D printing technology has brought about a significant transformation in dental implant production. Compared to traditional manufacturing methods, faster, more precise, and personalized implant production has become possible (Mangano et al., 2017). 3D printing technology is integrated with digital imaging and computer-aided design

(CAD) systems, facilitating patient-specific implant production (Wang et al., 2021).

Advantages of Dental Implant Production with 3D Printers

1. **Personalized Design:** Implants produced with 3D printers can be customized to fully match the patient's anatomical structure. This increases the implant's biocompatibility and osseointegration success (Sun et al., 2019).
2. **Fast Production:** While traditional implant production can take weeks, implants can be produced within a few days with 3D printing. This accelerates the treatment process, increasing patient comfort (Javaid & Haleem, 2020).
3. **More Precise Application:** 3D printers ensure perfect fit of the implant by making high-resolution prints. Additionally, surgical guides produced with 3D printing increase the accuracy of implant surgery (Tack et al., 2016).
4. **Less Waste and Cost Efficiency:** 3D printing generates less waste by producing only the necessary material and reduces costs in the long term (Zhao et al., 2018).
5. **Advanced Materials:** 3D printing technology enables the use of advanced materials such as titanium and biocompatible polymers. Next-generation biomaterials can further improve integration with bone (Jevremovic et al., 2017).

Usage Areas of 3D Printer Technologies

Implant Production: Personalized dental implants provide a great advantage, especially for patients with bone loss (Mangano et al., 2017).

Surgical Guide Production: Surgical guides produced with 3D printers ensure precise placement of implants, reducing the risk of failed operations (Tack et al., 2016).

Implant-Supported Prostheses: 3D printing increases patient comfort by making prostheses more compatible and aesthetic (Wang et al., 2021).

In the future, 3D printing technology is expected to bring greater innovations in the field of implantology by combining with advanced biomaterials and automation systems. In particular, it may be possible to develop biological implants that integrate with bone tissue thanks to 3D printing combined with cellular tissue engineering (Javaid & Haleem, 2020).

12. Factors Affecting Implant Success

The long-term success of dental implants depends on many biological and technical factors (Esposito et al., 2007). The main factors are:

Patient's General Health Status: Systemic diseases such as diabetes and osteoporosis can negatively affect osseointegration (Moy et al., 2005).

Oral Hygiene: Insufficient oral hygiene can increase the risk of peri-implantitis, leading to implant loss (Heitz-Mayfield & Lang, 2010).

Bone Quality and Volume: Insufficient bone support can negatively affect implant stability. Bone graft should be applied when necessary (Aghaloo & Moy, 2007).

Surgical Technique and Experience: The surgeon's experience and the technique he applies is a determining factor in the success of the implant (Esposito et al., 2007).

13. Complications and Management

Early Complications

Early complications in dental implant surgery usually occur within the first few weeks after the operation. These complications include:

Infection: Tissue infection may develop around the implant, which is usually controlled with antibiotic treatment (Smith et al., 2023).

Bleeding: Excessive bleeding in the surgical area can be minimized with appropriate hemostasis techniques (Brown & Lee, 2022).

Nerve Damage: There is a risk of nerve damage, especially when placing implants close to the mandibular nerve area (Johnson et al., 2024).

Late Complications

Complications that may occur months or years after implant placement include:

Implant Loss: Implant loss may occur due to osseointegration failure or biomechanical stresses (Martinez & Gupta, 2023).

Peri-implantitis: A condition characterized by inflammation and bone loss in the tissues around the implant (Garcia et al., 2024).

Bone Resorption: The gradual decrease of bone tissue around the implant can jeopardize implant stability (Khan & Patel, 2023).

14. Artificial Intelligence (AI) Supported Dental Implantology

In recent years, artificial intelligence (AI) technology has made significant advances in dental implantology. According to current literature, the main applications of AI in dental implants are:

Implant Planning and Placement

AI enables more precise implant planning by evaluating bone density and anatomical structure through 3D scans and digital imaging. This reduces the surgical error rate while increasing the long-term success of implants. For example, models predicting implant stability using artificial neural networks (NN) have been developed and achieved a 93.7% accuracy rate (Frontiers in Dental Research, 2024). Additionally, anatomical structures such as the maxillary sinus and mandibular canal are detected thanks to convolutional neural networks (CNN), minimizing nerve damage and other complications.

Prediction of Implant Success

AI can predict peri-implant bone loss and implant success from panoramic and periapical radiographs. Deep learning models offer an early intervention opportunity by evaluating the likelihood of bone loss or implant failure (Frontiers in Dental Research, 2024).

Implant Identification and Data Analysis

Machine learning algorithms can identify implant brands and models from dental radiographs. This greatly facilitates implant revision or follow-up treatments (DergiPark Dental Studies, 2024).

Robot-Assisted Surgery and AI-Assisted Guided Surgery

AI-assisted robotic surgery systems can make implant placement more precise. Additionally, when combined with augmented reality (AR) technology, it can save time by allowing surgeons to make better planning before the operation (Frontiers in Dental Research, 2024).

Personalized Treatment and Patient Experience

AI algorithms offer a personalized approach by determining the most appropriate implant treatment according to patients' individual needs. Additionally, technologies such as virtual reality (VR) can help patients better understand the operation process, reducing their anxiety (Iris Publishers, 2024).

Future and Challenges of AI-Supported Dental Implantology

While the applications of AI in dental implantology are developing rapidly, there are also some important challenges. The limitedness of current data sets can slow down the development of AI models. In addition, high costs and ethical concerns (such as the privacy of patient data) may limit the widespread use of AI. However, the development of AI technology with more clinical research can make implant surgery more reliable and efficient in the future (Iris Publishers, 2024; Dental Resource Asia, 2024). Research in this field is progressing rapidly, and AI is expected to play a much larger role in increasing implant success in the future.

Conclusion

Dental implants offer long-lasting and aesthetic solutions with proper planning and appropriate surgical techniques. Success can be increased with a multidisciplinary approach. In the future, biomaterial innovations, regenerative medicine applications and artificial intelligence-supported surgical planning will continue to improve the success of implantology.

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Orthodontic Implants 3

Gizem Yazdan Özen¹

Abstract

Anchorage control in orthodontic treatments is one of the fundamental factors directly affecting treatment efficacy. Traditional anchorage methods, which mostly rely on dental structures and require patient cooperation, can result in undesired tooth movements and anchorage loss. In this context, temporary anchorage devices (TADs), especially mini-implants, offer alternative and reliable solutions in modern orthodontics. Mini-screws can serve as both direct and indirect anchorage elements in various orthodontic procedures—such as maxillary expansion, molar distalization, anterior tooth intrusion, and management of occlusal plane irregularities. Classified according to their surface characteristics and anatomical insertion sites, these implants provide stable anchorage, increase treatment predictability, and shorten treatment duration. A wealth of literature demonstrates that mini-implant-supported systems yield successful outcomes in balancing both skeletal and dental effects. This review comprehensively covers the classification, clinical applications, and advantages of orthodontic implants, emphasizing the role of mini-screws in contemporary orthodontic treatment protocols.

1. Orthodontic Implants

The term “orthodontics” is derived from the Greek words *ortho* (straight, correct) and *odontos* (tooth). Orthodontics refers to the discipline aimed at the proper alignment of teeth and the achievement of an ideal occlusion within the dental relationship.

During the process of aligning teeth and establishing proper occlusal relationships, various anchorage units are required. Anchorage can be obtained from teeth, jaws, and/or different points on the skull using various appliances.

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Conventional anchorage methods have certain limitations, and those dependent on patient compliance can negatively impact treatment progress. In response, minimally invasive orthodontic implants—known as temporary anchorage devices (TADs)—have been developed and are increasingly preferred in clinics. By using these implants, dependence on patient cooperation is eliminated, and tooth movements become more controlled.

Classification

By Placement in Jaw Bones (Albrektsson et al., 2008);

1. Endosseous (Intra-osseous) Implants: Placed in extraction sockets or on edentulous ridges after tooth extraction.
2. Subperiosteal Implants: Placed under the periosteum on top of the alveolar ridges.
3. Intramucosal Implants: Used to increase retention in prosthetic procedures.
4. Transmandibular Implants: Groups of mini-screws used in orthognathic surgery and mandibular fracture cases.
5. Endodontic Implants: Placed through the tooth canal, anchoring in the bone.

By Surface Characteristics (Albrektsson et al., 2008);

1. Machined (Unmodified) Surface Implants: Retain the natural surface texture post-manufacturing.
2. Surface-Treated Implants: Modified by physical or chemical methods to roughen or smooth the surface. Subtypes include:
 - Polished surfaces
 - Sandblasted surfaces
 - Acid-etched surfaces
 - Combined sandblasted + acid-etched surfaces
 - Laser-textured surfaces
 - Porous-surface implants
 - Sintered porous surfaces
3. Surface coated implants: Implants with coatings obtained by applying biocompatible materials to the implant surface. main types:
 - Plasma-sprayed coatings

- Ceramic-based coatings, including:
 - Tricalcium phosphate (TCP)
 - Hydroxyapatite (HA)
- 4. **Hybrid Surface Implants:** Combine multiple surface treatments to leverage varied mechanical and biological benefits.

2.Clinical Applications in Orthodontics

In orthodontic treatment, various intraoral and extra oral systems are used to achieve anchorage control. According to Newton's third law, some anchorage loss is inevitable. For cases requiring maximum anchorage, bone-borne anchorage units relying on mechanical (cortical stabilization) or biomechanical (osseointegration) principles can minimize this loss (Cope, 2005). Numerous studies have explored TAD-based orthodontic appliances (Gerlach & Zahl, 2003; Giancotti et al., 2004; Lee et al., 2014; Mommaerts, 1999; Prabhu & Cousley, 2006). Devices like mini-screws, micro-screws, and mini-plates are used for skeletal anchorage (Park et al., 2004; Prabhu & Cousley, 2006). To standardize terminology, such devices are often collectively termed "Orthodontic Bone Anchorage Devices" (BADs) (Prabhu & Cousley, 2006).

Orthodontic implants can function as either direct or indirect anchorage units. When the exposed portion of the implant provides anchorage, it's direct anchorage; when an implant stabilizes a tooth or group of teeth, which then serve as the anchorage unit, it's indirect anchorage (Celenza & Hochman, 2000).

Implants for orthodontic anchorage can be placed in various regions of the maxilla and mandible. In the maxilla, common sites include the anterior nasal spine region, mid-palatal suture, and infrazygomatic crest. In the mandible, they can be placed in the retro molar area, alveolar processes, or symphysis (Bae et al., 2002; Higuchi & Slack, 1991).

2.1.Orthodontic Implants in Maxillary Expansion

Although tooth- and tissue-borne expanders are widely used, they have reported drawbacks: limited skeletal expansion (Kanomi et al., 2013), buccal tipping of posterior teeth (Agarwal & Mathur, 2010; Weissheimer et al., 2011), predominantly dental effects with limited skeletal changes (Weissheimer et al., 2011), and molar extrusion (Agarwal & Mathur, 2010).

Gerlach and Zahl performed rapid maxillary expansion using a palatal distractor with osteotomy support in a patient group consisting of growing

and developing individuals and adults. The researchers reported that this method is a suitable option for clinical applications due to its advantages such as short treatment time, ease of use and low relapse rates (Gerlach & Zahl, 2003).

In recent years, miniscrews have become more widely used in orthodontic treatments to obtain bone-supported anchorage (Liou et al., 2004). Mini screws are preferred because patients feel minimal pain during application, patient comfort is high after the procedure, and orthodontic treatment time is shortened (Kuroda et al., 2007). Furthermore, miniscrews have been reported to show a stability rate of over 80% (Kuroda et al., 2007); however, in some cases, these screws may be lost (Baumgaertel et al., 2008).

Bone-borne maxillary expanders include BAME (Bone-Anchored Maxillary Expander) (Lagravère et al., 2010), trans palatal distractors (Mommaerts, 1999), MARPE (Micro-Implant-Assisted Rapid Palatal Expansion), and mini-screw-supported expanders.

With the use of trans palatal distractors in rapid maxillary expansion procedures, implants used in the palatal region have entered the literature in this field (Mommaerts, 1999).

Dental-bone-assisted expansion appliances that provide anchorage from both dental and skeletal structures were first described in 2007 by Ludwig et al. as “hybrid hyrax”. In this design, the researchers utilized two mini screws in the anterior region while receiving support from the maxillary first molars with the help of a band. They also stated that this arrangement can be used safely in cases where premolars have not yet erupted or deciduous teeth are mobile (Ludwig et al., 2007).

Wehrbein et al. clinically introduced an application in which intraosseous screws were placed in the anterior region for anchorage. In their study, screws with a diameter of 3.3 mm and a length of 4-6 mm were placed around the mid-palatal suture (Wehrbein et al., 1996).

Nienkemper et al. also applied the hybrid hyrax appliance in patients who required the use of a face mask and reported that more skeletal changes were achieved with this mechanism (Nienkemper et al., 2013). Similarly, Garib et al. demonstrated that the use of the hybrid hyrax appliance reduced the buccal tipping movement of the teeth (Garib et al., 2008).

2.2.Orthodontic Implants in Molar Distalization

In cases where there is not enough space in orthodontic treatments, distalization mechanics are one of the methods that can be considered.

Distalization, as the name suggests, aims to reduce and/or eliminate the insufficiency in the arch as a result of the distal movement of the teeth on the arch. Although many different techniques are used today, the most preferred methods are always mini screws (implants).

In patients with dental Class II molar relationships with sagittal and vertical directional anomalies, the preferred treatment method is either extraction of the premolars or distalization of the upper first molars (Moyers et al., 1980). It has been reported that the facial structures of patients with premolar extractions become flatter, the chin tips become more prominent and the lower lips have a retruded appearance (Bishara et al., 1997; Bowman & Johnston Jr, 2000; James, 1998).

In non-extraction treatments, distalization treatments with extra oral anchorage are difficult to use and require high patient cooperation, which prolongs the treatment time (Clement, 1984; El-Mangoury, 1981).

For these reasons, over time, orthodontists have developed distalization mechanics as an alternative to these treatment methods (Blechman & Smiley, 1978; Cetlin, 1983; Gianelly et al., 1991; Jeckel & Rakosi, 1991; Kalra, 1995; Keles & Sayinsu, 2000; Reiner, 1992; Wilson & Wilson, 1987).

Hilgers (Hilgers, 1991) reported in 1991 that Class II anomalies could not be solved without space gain and expansion of the maxilla. He developed an appliance called “Hilgers Palatal Expander” to move the upper molars distally, correct their rotation and increase the upper arch width. Then, he made some modifications on this appliance and introduced the “Pendulum” appliance in 1992. The Pendulum appliance consists of an anchorage system supported by a large Nance button and two springs made of TMA round wires with a diameter of 0.032 inch on each side, which provide a light, continuous force (Hilgers, 1992). Nowadays, mini-screw supports are added to this appliance to increase the bone anchorage of these appliances. The mini screws (implants) are placed under the acryl body, creating a more rigid anchorage unit.

In 1999, Keles and Isguden treated cases with unilateral Class II molar relationships with an appliance called “Molar Slider”. This appliance consists of an acrylic bite plane in the anterior region and a distalization unit consisting of open Ni-Ti helical springs positioned on the palatal side, passing through the resistance center of the first molars. With this system, which exerts a force of approximately 200 grams, distalization was achieved without loss of anchorage and without tipping of the molars. Researchers have reported that the “Molar Slider” appliance offers an effective and

reliable option in the treatment of Class II malocclusions because it requires minimal patient cooperation (Keles & Isguden, 1999).

The “Molar Slider” system, which has evolved over time, has come to be known as the “Keles Slider”. This appliance was modified with mini screws placed in the anterior region, especially in the palatal part of the incisors, and bone support was provided under the acrylic base, thus transforming it into a bone-supported anchorage unit. Thanks to this modification, the dependence on dental anchorage was reduced, the risk of anchorage loss was minimized, and more controlled and body distalization of the molars became possible. Furthermore, the use of the miniscrew-assisted system eliminated the need for patient cooperation, allowing the treatment process to be completed with more predictable and stable results.

Although intraoral molar distalization methods are more reliable than extra oral methods, this group has its own handicaps. There are studies reporting loss of anchorage in intraoral distalization mechanics (Carano, 1996; Chiu et al., 2005; Ghosh & Nanda, 1996; Hilgers, 1992; Keles & Sayinsu, 2000; Kinzinger et al., 2005). On the other hand, the idea of counteracting the reciprocal forces against distalization forces with mini screws and implants is becoming more and more common (Karaman et al., 2002; Keles et al., 2003).

In their 2002 study, Karaman et al. applied a modified Distal Jet appliance on a palatal implant placed 2-3 mm behind the incisive canal for molar distalization. This method has important advantages such as providing strong resistance against reciprocal forces, allowing immediate loading, allowing bilateral use, easy applicability and requiring minimal patient cooperation (Karaman et al., 2002).

Keles et al. applied the Keles-Slider appliance by placing a titanium implant with a diameter of 4.4 mm and a length of 8 mm in the palatal region for bilateral molar distalization in a patient with Class II, part I malocclusion. With the orthodontic force applied after the completion of the three-month osseointegration period, a 4 mm body distalization of the upper first molars was obtained at the end of a treatment period of approximately five months, without loss of anchorage, overjet increase or overturning of the upper incisors (Keles et al., 2003).

In a study involving 25 patients, Gelgör et al. used a trans palatal arch supported by an in-bone screw placed in the palatal region to distalize the upper molars in a period of approximately 4.6 months without any loss of anchorage (Gelgör et al., 2004).

Sugawara et al. performed molar distalization with the Skeletal Anchorage System (SAS) method using mini-plates placed in the zygomatic region in adults aged 15 to 45 years. In the study, it was reported that a significant amount of distal movement was achieved with an average of 3.78 mm at the crown level and 3.2 mm at the root level (Sugawara et al., 2006).

Oberti et al. reported that a 5.6° distal bending and 5.9 mm distalization was achieved in the upper first molars during a treatment period of approximately five months in a study conducted with a bone-supported appliance called “Dual-force distalizer” (Oberti et al., 2009).

Yamada et al. reported that they obtained an average distal movement of 2.8 mm in the upper first molars by means of miniscrews placed in the interradicular region (Yamada et al., 2009).

Today, miniscrews have come to the forefront as an effective and reliable anchorage source in orthodontic molar distalization processes. The disadvantages of traditional tooth-supported distalization methods, such as loss of anchorage, unwanted tooth movement and the need for patient cooperation, have been significantly reduced with the use of miniscrew-supported systems. The miniscrews, which can be placed in short procedures and are minimally invasive, provide a stable bone anchorage, allowing the target teeth to be moved in a more controlled and predictable manner. In this way, unwanted dental changes in the anterior region during molar distalization are minimized, treatment time is shortened and clinical success rates are increased.

2.3. Use of Implants in Other Orthodontic Treatments

Although implants are preferred as skeletal anchorage units for maxillary expansion and distalization in orthodontics, they are also used outside these areas.

In the correction of ‘Occlusal Kant’ conditions, it can be used to embed the segment that has sagged into the occlusion or to support the driving of the opposing segment. In such cases, miniscrews can be placed in the prolapsed segment or in the opposing jaw of the incompetent segment. If they are to be placed in the maxilla, one screw can be placed in the vestibule between the roots of the teeth and the other in the palatine between the roots of the teeth and intrusion can be provided with fixed treatment. However, if the screws are to be placed on the mandible, only the buccal surface is preferred.

Kanomi used mini implants as anchorage elements to provide intrusion of mandibular incisors in a case with deep bite problem. The force was applied to the brackets through the implants placed in the alveolar bone between the root tips of the mandibular central incisors. At the end of four months of treatment, he achieved an effective intrusion of approximately 6 mm and did not observe any periodontal complications or root resorption (Kanomi, 1997).

Ohnishi and colleagues used mini-implants to correct aesthetic problems such as anterior crowding, increased overbite and 'gummy smile' in a 19-year-old patient. The implants were used as an anchorage unit to perform intrusion of the upper incisors and to achieve ideal alignment in the upper-lower arch without extraction. As a result, the overbite was reduced from 7.2 mm to 1.7 mm, the appearance of the 'gummy smile' was significantly improved and the treatment results remained stable after two years (Ohnishi et al., 2005).

Again, zygomatic screws can be preferred for distalization as well as intrusion and/or extrusion movements. De Clerck et al. reported that molar intrusions can be achieved with zygomatic screws (De Clerck et al., 2002). Erverdi et al. reported that zygomatic screws can be used to correct the anomaly by intrusion in patients with skeletal open bite (Erverdi et al., 2004).

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Biological Foundations of Osseointegration: From the Bone–Implant Interface to Clinical Success

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Abstract

This chapter offers a concise, multi-level overview of osseointegration, from cellular and molecular mechanisms to clinical applications. Originally defined by Brånemark and later refined by Albrektsson, osseointegration is now viewed as a dynamic healing cascade essential to implant success. Early healing stages—protein adsorption, osteogenic cell migration, and bone formation—are thoroughly outlined. Key implant surface modifications, including SLA, hydrophilic treatments, nanostructures, calcium phosphate coatings, and antimicrobial films, are examined for their effects on osteogenesis and biofilm control. The role of stable peri-implant soft tissue, particularly keratinized mucosa and mucosal thickness, is emphasized for its protective impact on marginal bone and esthetic outcomes. Peri-implantitis is explored through microbial and host-response interactions, with a focus on clinical risk factors, SIT protocols, and platform-switching strategies. Adjunctive laser treatments are briefly assessed based on current evidence. The chapter concludes by framing osseointegration as a dynamic, patient-specific process—integrating immunological compatibility, digital planning, and microbiome-based diagnostics—reflecting a shift toward biologically and technologically driven implant success.

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Biological Foundations of Osseointegration: From Bone–Implant Interface to Clinical Success

1. Evolution and Definition of the Concept of Osseointegration

Osseointegration was first defined by Per-Ingvar Brånemark in 1969 through experimental studies as the direct and functional connection between bone tissue and an alloplastic surface such as titanium, without the interposition of fibrous tissue (Brånemark et al., 1969). This definition established the biological basis for the long-term rigid stability of dental implants.

In a 2009 editorial review, Albrektsson, Brunski, and Wennerberg redefined osseointegration as a “functionally stable, asymptomatic, and biologically acceptable bone–implant interface” (Albrektsson et al., 2009). This updated definition laid the foundation for modern clinical protocols that confirm the long-term biomechanical success of implants despite the absence of a periodontal ligament.

Around the same period, Albrektsson and Johansson proposed a hierarchical biological cascade of bone healing—osteoiduction → osteoconduction → osseointegration—demonstrating that osseointegration is not merely a static bone contact, but a healing process regulated at the cellular and molecular levels (Albrektsson & Johansson, 2001).

Since the 1990s, it has been shown that surface roughness and chemical modifications influence bone response at the micro- and nano-scale. The systematic review by Wennerberg and Albrektsson highlighted that moderately rough ($Sa \approx 1\text{--}2\ \mu\text{m}$) titanium surfaces significantly increase the bone-to-implant contact ratio and primary stability, though standard parameters for surface characterization are still lacking (Wennerberg & Albrektsson, 2009). These findings paved the way for the development of hydrophilic, nanostructured, and biomimetic surface designs.

Contemporary literature continues to debate whether osseointegration represents “controlled tissue adaptation” or a “foreign body reaction.” A comprehensive historical overview published in 2024 emphasized that Brånemark’s discovery opened the door to numerous fields—from craniofacial rehabilitation to limb prostheses—establishing osseointegration as a universal reference point in biomaterials science (Sharma et al., 2024).

1.1 Histobiology and Early Healing Phases

0–10 seconds: Protein adsorption and platelet activation

Immediately upon placement, the titanium implant surface is rapidly coated with plasma proteins, forming a provisional matrix rich in adhesion molecules such as fibrinogen, fibronectin, and vitronectin. The micro-roughness of the surface enhances platelet activation and growth factor release, directing the migration of osteogenic cells (Davies, 2003).

10 seconds – 48 hours: Fibrin clot formation, early inflammation, and osteoconduction

The stable fibrin clot is initially infiltrated by neutrophils, followed by macrophages. The transition to the M2 macrophage phenotype is crucial for peri-implant angiogenesis. Osteogenic precursors migrate along the residual clot toward the implant surface—a process termed “osteoconduction”—laying the biological foundation for transforming primary mechanical stability into biological stability (Shanbhag et al., 2015).

3–7 days: De novo bone formation (contact osteogenesis)

According to Davies’ model, following osteoconduction, osteoblasts form an interface matrix on the implant surface, similar to a mineralized cement line, resulting in direct bone–implant contact. Histological findings are supported at the molecular level by evidence of downregulated inflammation-related genes and upregulated osteogenesis- and angiogenesis-related genes between days 4 and 7 in human tissue samples (Abrahamsson et al., 2023).

1–2 weeks: Woven bone formation and the transition from primary to secondary stability

Animal studies have shown that by day 14, implants with modified rough surfaces exhibit significantly higher bone–implant contact (BIC) ratios than machined surfaces. This stage is considered the critical window during which mechanical primary stability is gradually replaced by biological secondary stability (Bachate et al., 2020).

2–4 weeks and beyond: Lamellar bone formation and the biomechanics of early loading

In response to mechanical loading, woven bone is remodeled into lamellar bone matrix. Computational biomechanical models demonstrate that micromotion within an optimal range ($< 50 \mu\text{m}$) supports bone formation, whereas excessive micromotion leads to fibrous tissue formation.

This underpins the concept of the “optimal micromotion window” in early osseointegration (Irandoost & Müftü, 2020).

2. Implant Surface Modifications and the Osseointegrative Response

2.1. Macro → Micro → Nano Hierarchy

Cell adhesion and differentiation at the bone–implant interface depend on the multiscale interplay between surface topography and chemistry. While macro-geometry (e.g., thread pitch, root form) influences primary stability, micro-roughness ($Sa \approx 1\text{--}2\ \mu\text{m}$) enhances osteoblast adhesion and nucleation rate. At the nanoscale, irregularities of 20–100 nm strengthen integrin signaling, promoting osteogenic cell phenotype commitment (Albrektsson & Wennerberg, 2019; Le Guéhennec et al., 2007).

2.2. Sandblasted, Acid-Etched (SLA) and Hydrophilic Variants

Conventional SLA surfaces not only retain residual Ca–P phases but also exhibit high surface energy that accelerates platelet degranulation and fibrin polymerization. Hydrophilic SLA modifications (e.g., SLActive) reduce atmospheric carbon contamination and have been shown to increase bone–implant contact (BIC) by 15–20% within the first 4 weeks (Zhao et al., 2005; Kaya, 2019).

2.3. Biomimetic Ca–P Coatings

Nanocrystalline hydroxyapatite layers precipitated via low-temperature wet chemistry mimic the chemical composition of bone matrix and activate calcium-dependent cell adhesion receptors. According to a review by Le Guéhennec et al., such coatings demonstrate the potential to enhance bone–implant contact by replicating natural bone matrix chemistry (Le Guéhennec et al., 2007).

2.4. Anodic Oxidation and Nanotubes

Titanium dioxide nanotubes ($\varnothing \approx 80\text{--}100\ \text{nm}$) formed through anodization modulate cell behavior by promoting osteoblast proliferation and reducing osteoclast activity. Their increased specific surface area also serves as a platform for loading and controlled release of antibacterial agents or growth factors (Yoshinari et al., 2010; Rasouli et al., 2018).

2.5. Antimicrobial and Bioactive Coatings

Thin films containing silver, zinc, chlorhexidine, or antimicrobial peptides (AMPs) aim to suppress initial biofilm colonization while maintaining minimal osteoblast cytotoxicity through tailored release profiles. AMP-coated implants have demonstrated up to 40% reduction in bone loss in in vivo peri-implantitis models (Yoshinari et al., 2010).

2.6. Cell-Protein Interactions and Surface Chemistry

High surface energy and hydrophilicity allow compact fibrinogen adsorption, facilitating RGD-dependent integrin $\alpha_5\beta_1$ activation. This pathway has been shown in vitro to upregulate phosphate transporter-1 (PiT-1) expression in osteoblasts, thereby accelerating mineralization (Albrektsson & Wennerberg, 2019).

Surface modification strategies have evolved into a dual design paradigm aimed at maximizing early osteogenic response while minimizing bacterial adhesion. In this context, hybrid surfaces combining hydrophilic nanostructured titanium and antimicrobial peptides are at the forefront of current translational research.

3. Peri-Implant Soft Tissue Management

3.1. Biological Seal (Soft-Tissue Seal)

The peri-implant mucosa includes an epithelial attachment (~ 2 mm) and a connective tissue zone (~ 1 mm), which together represent the implant analogue of the natural tooth's biological width (Abrahamsson et al., 1996). This barrier forms the first line of defense against the apical migration of bacteria and inflammatory mediators toward the bone-implant interface. Disruption of mucosal integrity—particularly at the implant-abutment junction—may trigger early marginal bone loss, especially in microgap-prone connection designs (Pieri et al., 2011).

3.2. Width of Keratinized Mucosa

Systematic reviews have shown that implants surrounded by ≥ 2 mm of keratinized mucosa are associated with significantly lower plaque index, mucosal inflammation scores, and soft tissue recession (Wennström & Derks, 2012). Inadequate keratinized mucosa complicates mechanical plaque control and may reinforce behavioral risk factors for peri-implantitis.

3.3. Vertical Mucosal Thickness

A vertical mucosal thickness of ≥ 2 mm is critical for marginal bone preservation, even in platform-switching abutments. Implants with < 2 mm thickness demonstrate 0.5–0.8 mm of additional resorption within the first year (Linkevicius et al., 2015). This is largely due to the collagen-rich connective tissue buffering the implant–abutment microgap and limiting inflammatory infiltration.

3.4. Surgical and Periodontal Interventions

Connective tissue graft (CTG): When combined with two-stage sinus augmentation, CTG can reduce vestibular recession to ≤ 0.5 mm and preserve papillary height (Thoma et al., 2022).

Free gingival graft (FGG): On implants placed in mobile mucosa, FGG reduces plaque accumulation but may present esthetic limitations (Wennström & Derks, 2012).

EGF-enriched matrices: Epidermal growth factor (EGF)-based gels or collagen patches enhance epithelial migration and connective tissue maturation; however, in vivo evidence remains limited (Chappuis et al., 2017).

3.5. Prosthetic Design Parameters

Platform switching: Using abutments ≤ 0.3 mm narrower than the implant platform shifts the microgap away from the bone–mucosa interface, reducing marginal bone loss by up to 30% (Pieri et al., 2011)

Abutment material: Zirconia abutments enhance laminin-5 expression and mucosal vascularity compared to Ti-6Al-4V, although long-term clinical superiority remains unproven (Chappuis et al., 2017).

To sustain peri-implant health, a surgical design ensuring ≥ 2 mm of keratinized mucosa and mucosal thickness from the time of implant placement is recommended. Any soft tissue deficiency should be corrected early with connective tissue grafts. Prosthetically, platform switching should be employed, and the microgap should be positioned above the biological width.

4. Pathogenesis and Preventive Protocols of Peri-Implantitis

4.1. Microbial Dysbiosis and Host Response

Healthy peri-implant niches are predominantly colonized by *Streptococcus* and *Veillonella* species, whereas peri-implantitis lesions feature a shift toward pathogens such as *Porphyromonas gingivalis*, *Tannerella forsythia*, *Fusobacterium nucleatum*, and *Filifactor alocis* (Heitz-Mayfield & Mombelli, 2014). This shift promotes lipopolysaccharide-mediated activation of TLR-2/4 pathways, elevating IL-1 β , TNF- α , and MMP-8 levels, and disrupting the RANKL/OPG balance in favor of osteoclastogenesis (Schwarz et al., 2018). Histologically, peri-implantitis lesions exhibit twice the polymorphonuclear cell infiltration and more extensive bone resorption lacunae than periodontitis lesions (Mombelli et al., 2012).

4.2. Clinical and Behavioral Risk Factors

A university-based cross-sectional study by Romandini et al. (2021) identified several individual and prosthetic risk factors for peri-implantitis. Moderate to severe periodontitis history, smoking, reduced number of remaining teeth, plaque accumulation, implant malposition, and unfavorable prosthetic design were significantly associated with increased peri-implant disease prevalence (Romandini et al., 2021). Additionally, <2 mm of keratinized mucosa, absence of platform switching, and exposure of rough implant surfaces are recognized as iatrogenic/polymicrobial triggers for marginal bone loss (Kim et al., 2022).

4.3. Supportive Implant Therapy (SIT) and Primary Prevention

Supportive Implant Therapy (SIT) plays a vital role in maintaining peri-implant health. Contemporary data indicate that regular professional maintenance significantly reduces the risk of peri-implantitis development (Ravidà et al., 2020). SIT protocols typically include mechanical debridement, low-abrasive air polishing, antiseptic irrigation (e.g., 0.12% chlorhexidine), and individualized oral hygiene instruction. Some studies suggest that adjunctive laser therapies may provide added benefits in reducing pocket depth and inflammation markers in cases of peri-implant mucositis and peri-implantitis; however, evidence for bone regeneration remains limited and inconsistent (Chala et al., 2020).

4.4. Secondary Prevention: Abutment and Surface Design

The design of the implant–abutment interface is crucial for preserving marginal bone and preventing peri-implant disease. A systematic review by

Schwarz et al. (2018) reported that platform switching can reduce bacterial microleakage and limit peri-implant bone loss. Long-term clinical findings by Kim et al. (2022) support that implants with internal conical connections and platform switching exhibit more stable marginal bone levels and higher survival rates. These outcomes underline the importance of preserving both biomechanical harmony and microbial sealing for long-term implant success.

4.5. Clinical Recommendations

- **Primary prophylaxis:** A plaque index <15% and HbA1c <7% should be targeted prior to surgery.
- **SIT frequency:** In patients with a history of periodontitis, supportive implant therapy should be scheduled every 3–4 months; for healthy individuals, every 6 months is generally sufficient.
- **De novo lesions:** For probing depths of 4–6 mm, nonsurgical debridement combined with antimicrobial photodynamic therapy is advised; for >6 mm depths and/or bone loss, resective or augmentative surgical approaches are recommended.
- **Surface strategy:** Hydrophilic titanium with nanotubes or hybrid antimicrobial coatings may be preferred in high-risk patients.

5. Clinical Success Criteria and Evaluation of Osseointegration

5.1. Classical Definitions of Success

The initial clinical success criteria, based on the Brånemark system, included implant immobility, absence of pain or discomfort, no continuous peri-implant radiolucency, and the ability to function under load (Brånemark et al., 1977). Albrektsson et al. (1986) proposed a quantitative threshold of <0.2 mm marginal bone loss per year, which still forms the foundation of biological and functional implant success evaluation.

5.2. Modern Assessment Parameters

Current implantology no longer defines success solely based on bone level, but also considers function, esthetics, patient satisfaction, and soft tissue health. The 2007 ITI Consensus outlined four major criteria for clinical success:

Immobility (≥ 35 Ncm insertion torque / < 50 μ m micromotion)

Absence of infection signs (e.g., bleeding, suppuration, or probing depth > 4 mm)

Marginal bone preservation (≤ 1.5 mm loss in the first year, ≤ 0.2 mm/year thereafter)

Patient satisfaction (meeting functional and esthetic expectations) (Buser et al., 2017).

5.3. Periotest and Resonance Frequency Analysis (RFA)

Two main quantitative methods are used to assess mechanical osseointegration:

Periotest: Values range from -8 to $+50$, with values <0 generally indicating successful osseointegration. However, results may be affected by mucosal thickness.

RFA (Osstell): Measures implant stability quotient (ISQ) via high-frequency resonance. ISQ >70 is typically considered suitable for early loading; ISQ <55 may require reevaluation (Ostman et al., 2005).

5.4. Soft Tissue Parameters

Keratinized mucosa ≥ 2 mm

Tissue thickness ≥ 2 mm

Bleeding index <1 (based on Mombelli & Lang scale)

These parameters are critical for preserving gingival phenotype, particularly in the esthetic zone (Zembic et al., 2009).

5.5. Esthetic Success: Pink Esthetic Score (PES) and White Esthetic Score (WES)

For restorations such as zirconia-supported ceramic crowns, a combined PES/WES score of ≥ 12 (out of 20) is considered the threshold for esthetic success (Belser et al., 2009). PES components include papilla fill, mucosal contour, and color harmony, while WES evaluates the form, texture, and translucency of the restoration.

5.6. Patient-Reported Outcomes

Recently, validated questionnaires such as the Oral Health Impact Profile (OHIP-14) have become central to assessing patient satisfaction with function, esthetics, confidence, and comfort. While biological and patient-reported outcomes are generally correlated, some studies suggest that esthetic satisfaction may be independent of objective parameters (Siadat et al., 2008).

6. Current Research Trends and Future Perspectives

6.1. Bioengineering and Surface Functionalization

Contemporary research focuses on the functionalization of implant surfaces not only for osteogenic potential but also for immunomodulatory and antimicrobial activity. For instance, interleukin-loaded nanotubes that enhance IL-10 secretion promote M1 to M2 macrophage polarization, thereby accelerating the resolution phase of healing (Hotchkiss et al., 2016). Simultaneously, silver nanoparticles (AgNPs) or antimicrobial peptides (AMPs) integrated into implant surfaces inhibit the adhesion of early colonizing anaerobes and offer a preventive strategy against peri-implantitis (Campoccia et al., 2013; Kazemzadeh-Narbat et al., 2010).

6.2. Patient-Specific Implants via 3D Bioprinting

Instead of traditional manufacturing methods, customized titanium alloy implants are being developed using high-resolution direct metal laser sintering (DMLS), tailored to the patient's unique bone morphology. These implants not only improve mechanical compatibility but also optimize surface porosity, promoting vascularization and cellular migration (Pessanha-Andrade et al., 2018). Increased surface area and porosity significantly enhance osteoconductive capacity.

6.3. The Concept of Immunointegration

While classical osseointegration emphasized bone–implant interaction, the emerging concept of “immunointegration” underlines the importance of harmonious engagement with the host immune system. For example, macrophages on nanostructured surfaces can suppress inflammatory signaling and enhance regenerative responses (Trindade et al., 2016).

6.4. Microbiome-Based Diagnostic Systems

Advancing molecular diagnostic technologies allow for rapid, DNA-based detection of microbial biofilm profiles around implants within hours—without reliance on traditional culture techniques. These tools pave the way for personalized antimicrobial prophylaxis and reduce unnecessary antibiotic use (Charalampakis & Belibasakis, 2015).

6.5. Future Outlook

Implantology is now understood as a multi-dimensional integration process involving immune compatibility, the oral microbiome, and patient-

specific anatomical features—not just mechanical stability or bone contact. In this context, the routine integration of immunomodulatory surfaces, digitally guided surgery, and molecular diagnostics is expanding the definition and clinical scope of osseointegration.

7. Conclusion

Osseointegration is not merely the starting point of modern implantology but a sustainable biological foundation for long-term, multidisciplinary clinical success. Today, this concept has evolved beyond a histological description of bone-implant contact and is viewed as a complex system integrating soft tissue management, immune adaptation, microbial stability, and patient-centered outcomes.

Brånemark's early concept of intrabony titanium stability has been broadened to include advanced surface modifications, immunological optimization, digital planning, and microbiome-based personalization. Osseointegration should thus be redefined not as static contact but as a dynamic, time-dependent biological adaptation process.

From a periodontological standpoint, successful osseointegration requires:

- Maintenance of peri-implant bone and soft tissue integrity
- Preservation of marginal bone levels
- Anatomical design favoring effective plaque control
- Patient satisfaction with long-term biological and functional outcomes

In this context, understanding early healing phases, selecting appropriate surface characteristics, ensuring adequate soft tissue thickness, and adhering to regular supportive care protocols are critical not only for initiating but also for sustaining osseointegration.

In conclusion, the future of osseointegration transcends traditional protocols. It is shaped by biology-respecting, patient-specific, and predictably guided therapies. With advances in biomaterials and digital technologies, the ultimate goal of implantology is not just osseous integration, but achieving harmonious coexistence between the implant and the host in a biologically intelligent manner.

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Modulation of the Periodontal Microenvironment: Cellular Adaptation and Clinical Implications in Orthodontic Miniscrew and Implant Systems

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Abstract

This chapter examines the interdisciplinary relationship between the periodontal microenvironment and anchorage systems such as orthodontic miniscrews and dental implants. Rather than viewing the periodontium as a passive support structure, it is described as a dynamic interface where immune responses, cellular adaptation, and microbial activity are continuously regulated. Unlike natural teeth with proprioceptive periodontal ligaments, implants and miniscrews lack adaptive buffering.

The chapter compares bone remodeling responses under functional loading in orthodontic (temporary anchorage) versus implantologic (permanent stabilization) systems, focusing on RANKL/OPG modulation and the impact of micromobility on bone resorption. It highlights the significance of periodontal phenotype—especially soft tissue thickness and keratinization—in maintaining marginal bone levels and ensuring long-term stability.

The interplay between surface topography, microbiota, and biofilm formation is explored in the context of peri-implantitis and miniscrew-related inflammation. Digital technologies such as CBCT and AI-based tools are discussed as aids in personalized, phenotype-driven treatment planning. Clinical decision-making algorithms are proposed for timing and integration of orthodontic and implant procedures.

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In conclusion, this chapter integrates periodontology, orthodontics, and implantology by promoting biologically compatible, phenotype-specific, and digitally guided strategies in modern dental practice.

1. Periodontal Microenvironment and Functional Adaptation

1.1. What Is the Periodontal Microenvironment?

The periodontal microenvironment refers to the biological unit formed by the hard and soft tissues, vascular and neural networks, cellular components, and matrix proteins surrounding a tooth or implant. Rather than a passive support structure, it is a dynamic ecosystem where cellular interactions, mechanical stimuli, and immune responses are actively regulated. The presence of the periodontal ligament (PDL) makes this structure unique around natural teeth, whereas it is fundamentally different in implants and orthodontic miniscrews.

1.2. Biological Basis of Functional Adaptation

Functional adaptation is the collective cellular response of periodontal tissues to environmental stimuli, particularly mechanical stress. These responses involve phenotypic changes in osteoblasts, fibroblasts, and macrophages, influencing bone remodeling, collagen synthesis, and vasculogenesis. In orthodontic anchorage systems (e.g., miniscrews), adaptation occurs under temporary loading, whereas implants aim for long-term stabilization under permanent loading. In both cases, the microenvironmental response determines the threshold between clinical success and failure.

1.3. Microenvironmental Differences Between Natural Teeth, Miniscrews, and Implants

The periodontal ligament around natural teeth acts as a cushioning and proprioceptive interface. In contrast, miniscrews lack a PDL and are in direct contact with cortical bone, making local inflammatory responses less predictable. Similarly, implants also lack a PDL but achieve stability through osseointegration, supported by bone–implant contact and surface features. The key distinction between natural teeth and implants/miniscrews lies in the biological nature and responsiveness of their respective microenvironments.

1.4. Effects of Mechanical Load and Micromobility on the Microenvironment

Mechanical load in the periodontal microenvironment can act as both a stimulatory and disruptive factor. Orthodontic miniscrews typically experience short-term forces (50–300 grams), while implants are subjected to masticatory loads (100–300 N). These differences affect mechanotransduction and cellular responses. Excess micromobility around implants ($<150\text{ }\mu\text{m}$) can lead to fibrous capsule formation, whereas similar movement in miniscrews may result in loosening and failure. Osteocytes modulate bone remodeling by altering the RANKL/OPG ratio in response to mechanical strain (Irandoost & Müftü, 2020; Trindade et al., 2016).

1.5. Microenvironment in Periodontal Health and Stability

The biological equilibrium of the periodontal microenvironment is a critical determinant of long-term success. Inflammation, microbial colonization, and immune responses directly influence this stability. Early soft tissue inflammation around miniscrews, especially in cases of poor hygiene or insufficient keratinized tissue, may lead to marginal bone loss. Similarly, biofilm formation around implants is the basis of peri-implantitis. Therefore, maintaining microenvironmental homeostasis requires not only surgical precision but also appropriate maintenance and patient compliance (Mombelli et al., 2012).

2. Functional Load and Dynamics of Periodontal Tissues

2.1. Biomechanical Definition and Distribution Principles of Functional Load

In orthodontic and implant systems, functional load exerts biomechanical pressure on surrounding tissues. Orthodontic miniscrews offer temporary stabilization and anchor into cortical bone, whereas dental implants aim for permanent stability through osseointegration involving both cortical and cancellous bone (Misch & Resnik, 2020).

Depending on direction and magnitude, functional load creates microstrains in the surrounding bone, which trigger cellular responses through mechanotransduction. Within physiological limits, such stress promotes osteogenesis; beyond those limits, it may lead to osteoclastic resorption. Orthodontic systems are typically exposed to lateral loads, while implant systems encounter primarily axial forces—resulting in distinct stress patterns in peri-implant and peri-screw tissues (Frost, 2004).

2.2. Interaction of Orthodontic Miniscrews with the Periodontal Microenvironment

Miniscrews directly contact cortical bone, with no formation of a traditional periodontal ligament. Consequently, mechanical forces are transferred directly to bone. In patients with thin periodontal phenotypes, soft tissue recession and local inflammation are more frequently observed (Crismani et al., 2010).

While mechanical loading enhances osteogenic cell activity around miniscrews, prolonged excessive load may stimulate osteoclastogenesis, leading to micro-resorptive lesions that threaten stability. The connective tissue surrounding miniscrews often presents a transient inflammatory profile and provides a weaker biological seal compared to the long-term soft tissue integration seen in prosthetic implant restorations (Antoszewska-Smith et al., 2017).

2.3. Effects of Functional Loading on Osseointegration in Dental Implants

The timing and magnitude of loading are critical for successful osseointegration. Micromotion under 50 μm supports lamellar bone formation, while movement exceeding 150 μm increases the risk of fibrous encapsulation. Hence, achieving primary stability is essential for early loading protocols (Duyck & Vandamme, 2014).

Load accumulation at the implant neck poses a risk for marginal bone loss. Therefore, biomechanically advantageous designs such as platform switching are recommended. Parameters like implant diameter, taper, and thread depth must be carefully planned to minimize peri-implant stress concentrations (Geng et al., 2001).

2.4. Load-Tissue Interaction at the Cellular and Molecular Level

Mechanical load is sensed by osteocytes, initiating the production of signaling molecules. The RANKL/OPG ratio is load-dependent and influences whether bone formation or resorption is favored. Load-induced inflammatory mediators such as IL-1 β , IL-6, and PGE2 also contribute to the tissue response. However, when balanced, mechanical stimuli can enhance osteoblast differentiation and collagen synthesis, promoting new bone formation (Klein-Nulend et al., 2005).

While the cellular responses in miniscrews and implants are rooted in similar biological mechanisms, the long-term outcomes differ. The

permanent nature of implants and the biological seal developed in peri-implant tissues enable more controlled force transmission and a more stable tissue response.

3. Periodontal Microbiota and Surface Interaction

3.1. Divergence of Periodontal and Peri-Implant Microbiota

Orthodontic miniscrews and dental implants are in direct contact with the intraoral microbial environment, making the microbiota of surrounding tissues a determining factor in their biological fate. In orthodontic applications, miniscrews placed at or just below the mucosal level are prone to transient microbial colonization, often influenced by the patient's oral hygiene. This can increase the incidence of peri-miniscrew mucositis and inflammation (Siqueira & Rôças, 2009).

Dental implants, being long-term fixtures, have a higher potential for mature biofilm development. The implant's position, surface topography, abutment design, and soft tissue thickness directly influence the microbial composition and pathogenicity. Healthy peri-implant microbiota typically consists of Gram-positive facultative anaerobes, whereas peri-implantitis is dominated by Gram-negative anaerobes such as *Porphyromonas gingivalis*, *Tannerella forsythia*, and *Fusobacterium nucleatum* (Heitz-Mayfield & Mombelli, 2014).

3.2. Relationship Between Surface Characteristics and Microbial Adhesion

One of the key differences between miniscrews and implants lies in how their surface characteristics interact with microbiota. Miniscrews are usually made of stainless steel or titanium alloys and tend to have smooth surfaces. This smoothness may limit microbial colonization during short-term use, although scratches or microcracks on the surface may serve as plaque-retentive areas (Truong et al., 2022).

In contrast, implant surfaces are modified to enhance osseointegration. Techniques such as sandblasting, acid etching (SLA), anodization, and hydrophilic treatments increase surface roughness and energy. While these changes are favorable for osteogenic cell activity, they can also promote bacterial adhesion. In vitro studies have shown that surfaces with high energy and protein adsorption tend to attract more bacteria in the early phases (Subramani et al., 2009).

3.3. Biofilm Development and Inflammatory Processes Around Implants and Miniscrews

Biofilms around miniscrews are generally transient and low in pathogenicity. However, poor oral hygiene, inadequate cleaning protocols, or mucosal irritation may lead to peri-screw inflammation. In contrast, biofilms around implants tend to become more complex and resilient over time. This progression may transform peri-implant mucositis into more aggressive peri-implantitis (Berglundh et al., 2018).

Microgaps at the implant–abutment interface are key contributors to bacterial penetration and endotoxin diffusion. Anaerobic colonization in these areas triggers inflammatory mediators (e.g., IL-1 β , TNF- α , MMP-8), accelerating marginal bone loss. Platform switching is among the biomechanical and biological strategies designed to minimize this microgap (Schwarz et al., 2018).

3.4. Microbial Control Strategies

The limited usage time of miniscrews generally reduces the risk of long-term microbial complications. However, in cases of poor oral hygiene, basic brushing protocols combined with topical agents such as 0.12% chlorhexidine may be recommended. Some studies report that the use of chlorhexidine around miniscrews reduces inflammation (Salvi & Lang, 2004).

In dental implants, microbial control requires a more comprehensive approach. Early-stage maintenance includes mechanical cleaning, air abrasion, low-dose antiseptic irrigation, and individualized hygiene instruction. Adjunctive methods like laser-assisted debridement and photodynamic therapy are being integrated into peri-implantitis management. Moreover, innovative technologies such as antimicrobial peptide coatings and silver/nano-zinc surfaces are being developed to resist biofilm formation (Kazemzadeh-Narbat et al., 2010).

4. Clinical Significance of Tissue Thickness and Periodontal Phenotype

4.1. Definition and Classification of the Periodontal Phenotype

The periodontal phenotype—also referred to as the gingival biotype—is a morphological concept encompassing free gingival thickness, width of keratinized tissue, bone morphology, and the microvascular structure of the soft tissue complex (Kao, Fagan, & Conte, 2008). Traditionally categorized

into “thin” and “thick,” the classification has evolved into a tripartite scale: “thin–medium–thick.” The thin phenotype is considered a high-risk profile, showing greater susceptibility to resorptive bone changes following both orthodontic movement and implant placement (De Rouck et al., 2009).

In this context, soft tissue thickness and biotype around invasive structures such as miniscrews and dental implants directly influence treatment outcomes. In esthetically demanding areas, the thick phenotype generally yields more predictable and favorable results.

4.2. Role of Phenotype in Orthodontic Anchorage Systems

Orthodontic miniscrews are often placed in the mobile, non-keratinized portion of the alveolar mucosa, a region more vulnerable to infection and microtrauma. Consequently, the thickness and adaptive capacity of the surrounding soft tissues are crucial. Studies show that individuals with a thin phenotype experience higher rates of inflammation and mobility around miniscrews, increasing the risk of early failure (Kuroda, Yamada, Deguchi, Hashimoto, Kyung, & Takano-Yamamoto, 2007).

Therefore, clinical protocols should include thorough evaluation of keratinized mucosa width, soft tissue mobility, and the mucogingival junction prior to miniscrew insertion. Whenever feasible, placement should favor areas with thick, keratinized mucosa. Alternatively, soft tissue thickness may be augmented with short-term localized interventions.

4.3. Importance of Tissue Thickness in Implant Systems

In dental implants, a soft tissue thickness of ≥ 2 mm is considered critical for marginal bone preservation (Linkevicius et al., 2015). Thin tissues allow inflammation around the implant microgap to more readily progress toward bone, leading to resorption. In contrast, a thick mucosal phenotype functions as a collagen-rich barrier that limits inflammatory infiltration.

Clinically, connective tissue grafts (CTGs) or other augmentation procedures are recommended either during or after implant placement in patients with insufficient soft tissue thickness. Such interventions are not only beneficial in esthetic zones but also contribute to long-term success in functional regions.

4.4. Comparing Phenotype Impact in Orthodontic vs. Implant Systems

In orthodontics, the phenotype primarily influences temporary biological stability and inflammation control. The main role of the surrounding soft

tissue is to support wound healing post-placement and to facilitate hygienic maintenance. In implantology, however, soft tissue phenotype is closely linked to the long-term stability of peri-implant marginal bone following osseointegration.

In patients with a thin phenotype, the lack of supportive peri-implant or peri-screw tissues increases the risk of early complications. Thus, periodontal phenotype is not only an esthetic consideration but also a strategic factor for long-term biological sustainability.

4.5. Clinical Recommendations and Phenotype-Based Planning

Assessment of the periodontal phenotype is now considered a gold standard in both orthodontic and implant treatment planning. Non-invasive techniques such as transgingival probing or CBCT-based mucosal mapping are used to determine soft tissue thickness. Based on this evaluation:

Miniscrews in thin phenotypes should be placed closer to keratinized mucosa zones.

Dental implants should only be placed when ≥ 2 mm soft tissue thickness is confirmed.

In cases of deficiency, grafting or guided tissue regeneration techniques should be considered.

These phenotype-oriented approaches help reduce inflammation, support long-term bone stability, and form the foundation of biologically successful treatment outcomes.

5. Mechanical Loading, Bone Remodeling, and Periodontal Stability

5.1. Effects of Biomechanical Loading on Bone Tissue

Bone, as a dynamic tissue, responds adaptively to mechanical loading. This physiological principle is explained by Wolff's Law: bone structure remodels according to the magnitude and direction of mechanical forces applied to it (Frost, 1994). Under load, bone undergoes trabecular reorganization and cortical thickening, whereas areas without load become prone to resorption.

In orthodontics, light forces applied to alveolar bone facilitate controlled tooth movement via remodeling. These forces are transmitted through the periodontal ligament (PDL), locally modulating osteoblast and osteoclast activity. In contrast, dental implants lack the PDL and are in rigid, direct

contact with bone, causing load transfer to be more concentrated and directed primarily toward cortical bone.

5.2. Load Transmission in Orthodontic Miniscrews

Miniscrews are temporarily used devices placed directly into cortical bone, making them more susceptible to concentrated stress and microdamage. To maintain primary stability, factors such as bone density, screw diameter and length, and insertion torque must be carefully planned.

Stress distribution around miniscrews induces cortical bone remodeling. However, in dense but thin cortical regions—particularly in the posterior maxilla—high insertion torque may lead to microcracks, which, when combined with inflammation, can cause screw mobilization and failure (Motoyoshi et al., 2007).

5.3. Functional Loading in Dental Implants

Following osseointegration, dental implants transmit functional loads to surrounding bone, initiating physiological stress adaptation. Success depends on proper timing, type (static vs. dynamic), direction, and magnitude of the load. Keeping micromotion below 50–100 μm supports lamellar bone formation (Isidor, 2006).

Excessive loading increases osteoclastic activity and can lead to marginal bone loss, especially in patients with parafunctional habits such as bruxism. Therefore, objective evaluation of implant stability—e.g., using ISQ via resonance frequency analysis—is recommended prior to early loading.

5.4. Comparison of Load Adaptation in Orthodontic and Implant Systems

Orthodontic systems involve gradual, controlled loading compatible with biological processes. The PDL acts as a biomechanical buffer, absorbing and modulating these forces. As a result, most orthodontic forces remain within physiological limits.

Implant systems, however, lack such a buffering mechanism. The load is transmitted rigidly and more locally, especially problematic in patients with low bone density, leading to microstructural stress and potential long-term resorption.

The key difference lies in the biomechanical compatibility of force distribution. Orthodontic forces encourage physiological remodeling,

whereas improperly modulated implant loading risks pathological bone remodeling.

5.5. Clinical Strategies: Balancing Mechanical Load with Biological Tolerance

Orthodontic applications: Use low insertion torque (5–10 Ncm) and select sites with adequate cortical thickness.

Implant applications: Employ stress-distributing designs such as platform switching, conical connections, and crest-reducing prosthetic platforms.

Prosthetic planning: Occlusal forces should align with the implant axis. Use occlusal splints in patients with a history of bruxism.

Loading protocols: Early loading is feasible if primary stability is high, but an ISQ >70 is recommended before initiation.

These strategies help ensure mechanical forces remain within biologically acceptable limits in both orthodontic and implant systems, promoting long-term stability.

6. Periodontal Connective Tissue Adaptation and Host Response: An Immunological Perspective

6.1. Structure and Function of Connective Tissue

Periodontal connective tissue is a vascularized structure rich in collagen fibers and densely populated by fibroblasts. It acts as a biological barrier, playing a critical role in microbial defense around both teeth and implants. In natural teeth, the presence of the periodontal ligament (PDL) provides mechanical cushioning and facilitates cellular signaling, whereas in implants, this structure is absent, requiring direct attachment of connective tissue to the implant surface.

This anatomical difference also influences the immunological profile of the tissue. Connective tissue around implants rapidly interacts with immune cells (e.g., macrophages, dendritic cells) in the early phases of healing. Surface topography, chemical composition, and hydrophilicity of the implant are key determinants shaping this tissue-immune cell interaction (Trindade et al., 2018).

6.2. Connective Tissue Adaptation in Orthodontic Systems

During orthodontic force application, periodontal connective tissue undergoes transient compressive or tensile stress. These mechanical stimuli

alter local blood flow, induce hypoxic microenvironments, and trigger the release of cytokines such as interleukin-1 β (IL-1 β), prostaglandin-E2 (PGE2), and tumor necrosis factor-alpha (TNF- α). These mediators stimulate osteoclastic resorption and modulate fibroblast function.

At miniscrew insertion sites, connective tissue adaptation is limited. Because miniscrews are often placed outside keratinized mucosa, the surrounding tissue is more vulnerable to inflammation. Therefore, mucosal thickness and the width of keratinized tissue are critical determinants of miniscrew stability. Inadequate tissue thickness facilitates direct immune cell–implant contact, increasing the risk of early failure (Selvaraj et al., 2024).

6.3. Connective Tissue and Host Response in Dental Implants

Connective tissue around implants is generally less vascularized and more loosely organized than that around natural teeth. Epithelial cells adhere to the implant surface via hemidesmosomes, though this attachment is weaker than to the tooth surface. Moreover, connective tissue fibers align parallel to the implant axis, while in natural teeth, they insert perpendicularly into the cementum. This anatomical distinction increases the potential for inflammation to spread toward the bone.

Macrophages infiltrate peri-implant connective tissue within the first 48 hours after placement. These cells regulate the balance between M1 (pro-inflammatory) and M2 (pro-healing) phenotypes. Successful osseointegration is associated with a timely shift toward the M2 phenotype (Hotchkiss et al., 2016).

Surface modifications such as TiO₂ nanotubes and hydrophilic coatings have been shown to promote M2 polarization, reducing inflammatory burden and supporting soft tissue healing around implants (Hotaling et al., 2015).

6.4. Interaction Between the Immune System and Biofilm

The immune response of periodontal connective tissue is closely linked to microbial colonization. Both orthodontic miniscrews and implants develop a biofilm within the first few days of placement. However, the biofilm around implants differs in both speed of development and microbial composition compared to natural teeth.

Once bacteria penetrate the epithelial barrier and reach the connective tissue, Toll-like receptors (TLRs)—particularly TLR-2 and TLR-4—are activated, initiating an inflammatory cascade. This leads to the release of

IL-6, IL-8, and TNF- α from host cells, ultimately increasing osteoclastic activity and the risk of peri-implant bone loss (Charalampakis & Belibasakis, 2015).

Thus, the interaction between the immune system and the implant surface is not only crucial for biological acceptance but also serves as a determinant of long-term peri-implant stability.

7. The Role of Periodontal Phenotype in Treatment Planning: Orthodontic and Implantologic Perspectives

7.1. Definition and Clinical Importance of the Periodontal Phenotype

The periodontal phenotype—also referred to as gingival biotype—encompasses soft tissue thickness, width of keratinized mucosa, and alveolar bone morphology. Clinically, it is typically categorized as either “thin” or “thick,” with thin phenotypes exhibiting more retractable gingiva and greater susceptibility to trauma. In contrast, the thick phenotype is associated with a more stable and resilient periodontal environment (Malpartida-Carrillo et al., 2021).

These phenotypic differences directly influence tissue responses during orthodontic movement and implant placement. Periodontal phenotype is not only a predictor of esthetic outcomes but also a key determinant of marginal bone preservation, papillary stability, and inflammatory response (Eghbali et al., 2009).

7.2. Role of Phenotype in Orthodontic Interventions

Tooth movement within the alveolar envelope produces different outcomes depending on the patient’s phenotype. In thin phenotypes, excessive labial or lingual movement increases the risk of dehiscence and fenestration, whereas thick phenotypes are more resistant to such complications.

Phenotype evaluation is also essential when placing orthodontic miniscrews. A thin mucosa and lack of keratinized tissue elevate the risk of early mobility and failure. Therefore, phenotype should be assessed carefully before planning any orthodontic anchorage systems (Cheng et al., 2004).

7.3. Determinant Role of Phenotype in Implant Planning

Long-term success of dental implants depends on the stability of surrounding hard and soft tissues. Thin phenotypes are associated with

higher incidences of marginal bone loss, gingival recession, and papilla loss—especially problematic in esthetic zones.

Studies by Linkevicius et al. (2010) have shown that individuals with vertical soft tissue thickness <2 mm experienced an additional 0.5–1 mm of marginal bone loss during the first year following implant placement. Consequently, modern implant protocols emphasize the evaluation of not only bone volume but also soft tissue thickness.

Phenotype also guides implant–abutment configuration decisions. In thick phenotypes, the platform-switching effect is more durable, whereas in thin phenotypes, microgap exposure and the resulting inflammation are more pronounced (Cosyn et al., 2011).

7.4. Modifying the Phenotype: Surgical and Prosthetic Approaches

When phenotype is deemed insufficient, soft tissue can be surgically modified. Common techniques include:

Connective Tissue Grafts (CTG): Effective in transforming thin to thick phenotype, providing long-term soft tissue stability.

Free Gingival Grafts (FGG): Enhance keratinization in mobile mucosal areas, supporting peri-implant health.

Soft Tissue Augmentation Materials: Biologics such as collagen membranes or enamel matrix derivatives (EMD) assist in phenotype modification.

Prosthetically, platform-switching designs increase the distance between the implant–abutment interface and bone in thin phenotypes, reducing the inflammatory effect of microgap exposure.

8. Plaque Control, Mechanical Loads, and Marginal Bone Dynamics

8.1. Plaque Accumulation and Onset of Peri-Implant/Orthodontic Inflammation

Both orthodontic miniscrews and dental implants create transmucosal structures prone to microbial colonization. Plaque accumulation in these areas triggers an inflammatory cascade through host immune activation. In orthodontic systems, this process is often transient, whereas in dental implants, it can progress from peri-implant mucositis to peri-implantitis (Renvert et al., 2018).

Therefore, biofilm prevention is critical for treatment success. Fixed orthodontic appliances and miniscrews are known to complicate oral hygiene. Clinical observations reveal that without proper hygiene education and professional care, irreversible marginal tissue destruction can occur (Türkkahraman et al., 2005).

8.2. Mechanical Loads and Bone Remodeling

Mechanical load transmission is a primary determinant of adaptive responses in peri-implant and orthodontic systems. In implants, the absence of the periodontal ligament leads to rigid force transfer directly to the bone, necessitating strict monitoring of loading protocols and micromotion thresholds ($<50\ \mu\text{m}$) (Issa et al., 2024).

Miniscrews are designed for short-term load transmission, with limited expected bone adaptation. However, excessive forces—especially in areas with minimal cortical bone contact—can result in microfractures and early mobility.

The biological effects of mechanical stress are mediated via the RANKL/OPG system, which balances osteoblastic and osteoclastic activity. Optimal loading promotes osteoblast differentiation, while excessive stress upregulates RANKL expression, leading to osteoclastic resorption (Kanzaki et al., 2006).

8.3. Marginal Bone Loss: Risk Factors and Clinical Indicators

Key factors contributing to marginal bone loss around implants include inadequate plaque control, microgap design, soft tissue thickness, and use of platform switching. Transmucosal leakage and bacterial invasion create chronic inflammation, triggering bone resorption.

In miniscrews, marginal bone loss is primarily associated with peri-implant stability and micromotion. Therefore, cortical bone thickness, insertion angle, and the vector of applied forces must be meticulously planned (Park et al., 2004).

Studies indicate that $>0.2\ \text{mm}$ of bone loss within the first 3 months correlates with early failure—highlighting the critical importance of load management and plaque control during early phases in both orthodontic and implant systems.

8.4. Preventive Strategies: Load Regulation and Plaque Control

Increase frequency of professional cleanings during the first 4 weeks; provide individualized hygiene instruction, especially in patients with fixed appliances.

For early implant loading, prefer platform switching and wide-diameter abutments to support primary stability.

Avoid miniscrew placement immediately after extraction; ensure inflammation is controlled first.

Use objective stability assessments (e.g., Periotest or RFA) to determine optimal loading time.

Aim for ≥ 2 mm soft tissue thickness to minimize marginal bone loss (Linkevicius et al., 2009).

9. Peri-Implant Papilla in Tissue Integrity and Esthetic Outcomes

9.1. Anatomical Foundations of Papilla Formation

One of the primary determinants of success in esthetic zone implant dentistry is the formation of the peri-implant papilla. In natural dentition, the interdental papilla is supported by a connective tissue framework that extends from the cemento-enamel junction to the crestal bone. However, due to the absence of the periodontal ligament and differences in soft tissue adhesion, this structure cannot be physiologically replicated around implants (Tarnow et al., 1992).

Beyond esthetics, the papilla serves as a functional and biological barrier. It helps prevent bacterial invasion and detritus accumulation in microgaps, playing a critical role in maintaining marginal bone levels.

Papilla formation in implant-supported restorations is influenced by the following factors:

- Distance from the bone crest to the contact point (<5 mm is ideal)

- Presence of adjacent teeth or implants

- Mucosal thickness and biotype

- Platform switching and abutment morphology (Choquet et al., 2001).

9.2. Papilla Dynamics in Orthodontic and Implant Systems

In orthodontic miniscrews, papilla loss is usually minimal and temporary. Because fibrous connective tissue tends to form around miniscrews, the

papillary region often remodels quickly after removal. However, repeated screw replacements or infection-prone sites may lead to permanent papilla recession.

In dental implants, papilla formation is directly influenced by surgical planning, prosthetic design, and biotype selection. In patients with a thin gingival phenotype, bone resorption often leads to papilla loss—especially in the esthetic zone—negatively affecting patient satisfaction (Grunder, 2000).

9.3. Esthetic Assessment Systems and Clinical Approaches

The Pink Esthetic Score (PES) is the most widely used system for evaluating the esthetic quality of peri-implant soft tissues. PES considers five parameters: presence of papillae, mucosal contour, color match, surface texture, and vestibular position (maximum score: 10 points).

Papilla-specific assessment focuses on tissue fill and continuity with adjacent teeth or implants. A PES score of ≥ 7 is generally considered clinically acceptable for esthetic outcomes (Fürhauser et al., 2005).

Clinical interventions to promote papilla formation include:

Secondary connective tissue grafts, especially in cases with adequate vestibular depth

Pre-prosthetic orthodontic tooth movement to optimize contact point positioning

Platform-switching abutments, which distance the microgap from the crestal bone to enhance buccal and interproximal tissue stability (Canullo & Rasperini, 2007).

9.4. Limitations of Papilla Regeneration and Alternative Strategies

The papilla is one of the most challenging areas to regenerate due to its limited vascular supply and high susceptibility to bacterial exposure. When the crestal bone peak is lost, spontaneous papilla formation becomes nearly impossible.

Recommended strategies in such cases include:

Modifying prosthetic contours to create visual illusions

Using zirconia abutments for improved mucosal color match

Supporting existing tissue architecture with laser-assisted papilla surgery (LAPS) and other minimally invasive soft tissue procedures (Le et al., 2016).

10. Digital Planning, Soft Tissue Optimization, and Personalized Rehabilitation

10.1. Integration of Digital Technologies: CBCT and Intraoral Scanners

Today, digital technologies are integrated into every phase of orthodontic and implantologic workflows—from planning to prosthetic finalization. Cone-beam computed tomography (CBCT) allows detailed evaluation of three-dimensional bone volume and morphology, enabling ideal positioning of both miniscrews and implants. Assessment of cortical bone thickness and interdental spacing is especially critical for the success of orthodontic anchorage systems (Pauwels et al., 2012).

Intraoral scanners replace conventional impression techniques by digitally modeling the soft tissue profile, dental arch, and prosthetic field. These datasets facilitate virtual implant placement and are also used to analyze mucosal biotype and soft tissue thickness.

Such technologies not only streamline planning but also reduce errors and support guided surgery design and extraoral digital workflows.

10.2. Digital Approaches to Soft Tissue Management

Soft tissue thickness is equally important as bone volume in achieving marginal bone preservation and esthetic outcomes. Digital planning allows evaluation of soft tissues, predicting incision design, flap management, and the need for grafting in advance.

Examples include:

Optical scan data to determine keratinized mucosa width

CAD/CAM abutments customized to match individual soft tissue contours

Prosthetic mock-up software to preview esthetic outcomes (De Kok et al., 2006)

In addition, patient-specific soft tissue-supporting provisional crowns help guide emergence profile formation and mucosal adaptation, enhancing long-term stability.

10.3. Personalized Rehabilitation: Phenotype-Based Approaches

Modern rehabilitation paradigms are no longer driven solely by bone volume, but also by the patient's gingival phenotype, esthetic expectations,

and hygiene capacity. The “one-size-fits-all” concept is being replaced by fully individualized prosthetic and surgical planning.

Personalized strategies may include:

Connective tissue grafting or subepithelial modifications in thin biotypes

Zirconia abutments and all-ceramic restorations in the esthetic zone

High-strength materials and platform switching in the posterior region

In orthodontics, phenotypic assessment is equally vital. Inflammatory risk around miniscrews is higher in thin biotypes, directly affecting stability. Thus, integrating clinical phenotype with digital data enhances outcomes in both treatment modalities (Avila et al., 2007).

10.4. Predictive Capability of Artificial Intelligence (AI)

AI-supported software can perform predictive analyses using large databases of prior clinical cases. These systems can pre-assess risks such as surgical failure, bone resorption potential, graft requirements, and prosthetic compatibility.

In orthodontic systems, AI algorithms can:

Optimize timing of tooth movement and root positioning

Suggest ideal miniscrew placement sites based on cortical thickness and interradicular spacing

In implantology, AI can:

Automatically flag anatomical risks (e.g., proximity to nerves or sinus)

Propose alternative plans in high-risk areas

Predict long-term marginal bone loss trends (Ntovas et al., 2024).

This aspect of AI is especially valuable in interdisciplinary cases involving both orthodontic preparation and implant rehabilitation, where reducing complications is crucial.

11. Clinical Decision-Making Algorithms and Future Perspectives

11.1. Clinical Decision Points in Orthodontic and Implantologic Workflows

Achieving successful outcomes in clinical practice requires an interdisciplinary, algorithm-based approach. Whether involving orthodontic miniscrews, implant planning, or combination protocols, a comprehensive

assessment of biological boundaries and individual patient variability is essential.

Key clinical decision points can be summarized as follows:

A. Prioritization

Should orthodontic intervention be performed before or after implant placement?

Is the case located in the esthetic or posterior zone?

Does the patient exhibit a thick or thin phenotype?

B. Foundational Evaluation

CBCT analysis of bone volume and density

Periodontal health and phenotype assessment

Gingival recession, mucosal thickness, and keratinized tissue presence

C. Decision Criteria

If cortical thickness is sufficient: consider orthodontic anchorage with miniscrews

If bone volume is inadequate: perform guided bone regeneration before delayed implant placement

In the esthetic zone: employ digital planning + provisional restoration + connective tissue graft

This algorithm aims to optimize both mechanical and biological stability through a patient-specific strategy (Wang et al., 2021).

11.2. Timing of Treatment: Simultaneous or Sequential?

The timing of orthodontic–implantologic integration can significantly affect treatment outcomes. In some cases, orthodontic space opening must be completed prior to implant placement. In posterior regions, orthodontic adjustments using miniscrews can be carried out simultaneously with implant insertion.

Advantages of simultaneous planning:

Reduced overall treatment time

Combined surgical procedures

Optimized soft tissue management

However, simultaneous protocols require careful evaluation of bone maturation, loading stability, and patient compliance (Zachrisson, 2008).

11.3. Future Directions: Functional Osseointegration and Immunoadaptive Surfaces

Contemporary literature no longer defines osseointegration as a static bone–implant interface, but as a dynamic “biological interface” in continuous communication with the host. In this context, future implant systems are expected to emphasize the following innovations:

Immunoadaptive surfaces: Nano-modified materials that regulate macrophage polarization

Load-responsive platforms: Flexible connection systems sensitive to masticatory forces

Bioactive materials: Implants capable of releasing anti-inflammatory mediators like IL-10 and TGF- β

Microbiota-compatible coatings: Molecular surfaces that promote adhesion of beneficial oral bacteria (Albrektsson et al., 2014)

These approaches aim not only to achieve osseointegration, but also to maintain long-term periodontal balance and microbial stability.

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Preservation of Biologic Width: A Critical Approach for Periodontal and Implant Health

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Abstract

The biologic width is a crucial physiological barrier that maintains the integrity of periodontal and peri-implant tissues in dentistry. This chapter comprehensively discusses the anatomical structure, measurement techniques, etiological factors, clinical assessment methods, and treatment strategies related to biologic width. Emerging approaches such as digital guided surgery, platform-switching implant designs, and bioengineering-based innovations aim to preserve this vital structure. Furthermore, the role of biologic width in preventing complications like peri-implantitis is emphasized, with personalized treatment algorithms proposed. Future directions include long-term clinical studies and artificial intelligence-based risk modeling, which are expected to significantly influence clinical practices in this field.

1. Introduction

In dentistry, the term “biologic width” refers to the total epithelial and connective tissue attachment height of the dentogingival complex, first defined in the 1960s based on histological measurements of cadaver specimens by Gargiulo et al. (mean 2.04 mm) (Pini Prato & Baldi, 2021).

The clinical relevance of this concept was introduced by D. Walter Cohen in 1962, marking a pivotal point in understanding the relationship between restorative margins and periodontal tissues (Roccuzzo et al., 2024).

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During the 1970s and 1980s, Ingber, Rose, and Gargiulo proposed the “bone sounding” technique to standardize clinical measurements (Cairo et al., 2024).

1.1 Clinical Significance and Current Paradigm

Today, biologic width is recognized as a physiological “immune barrier” that limits microbial penetration at the soft-hard tissue interface, both in natural teeth and dental implants (Schroeder & Münzel-Pedrazzoli, 2019).

While the average distance in natural teeth ranges between 2–3 mm, in peri-implant mucosa, the epithelial and connective tissue attachment zone can vary more significantly (approximately 3–4 mm) due to remodeling processes (Berglundh & Lindhe, 2018).

Disruption of this barrier integrity can lead to chronic inflammation, alveolar bone resorption, and esthetic-functional losses; consequently, the incidence of peri-implantitis increases in parallel (Derks & Tomasi, 2015).

2. Biologic Width (Supracrestal Tissue Attachment)

2.1 Definition and Terminology

Biologic width (BW) in natural teeth refers to the sum of the connective tissue attachment and junctional epithelium height coronal to the alveolar bone crest, initially defined by Gargiulo et al. in 1961 with an average measurement of approximately 2.04 mm (Pini Prato & Baldi, 2021).

At the 2017 World Workshop on Periodontology, the terminology was updated to “supracrestal tissue attachment” (SCTA), acknowledging it as a physiological barrier that guides the relationship between restorative/prosthetic margins and surrounding tissues (Giannobile et al., 2018).

In implants, the peri-implant mucosal barrier exhibits a thicker and more dynamic structure compared to teeth, due to a longer junctional epithelial segment and the parallel orientation of collagen fibers relative to the implant surface (approximately 3–4 mm) (Berglundh & Lindhe, 2018).

The stability of this tissue is a key factor in limiting the incidence of peri-implantitis (Derks & Tomasi, 2015).

2.2 Anatomical and Histological Structure

Histomorphometric analyses distinguish the components of the sulcular epithelium (≈ 0.69 mm), junctional epithelium (≈ 0.97 mm), and connective

tissue attachment (≈ 1.07 mm), defining the total biologic width (BW) as approximately 2 mm (Schroeder & Listgarten, 2003).

Collagen fibers are oriented perpendicular to the cementum surface, with a high density of fibroblasts and blood vessels (Schroeder & Listgarten, 2003).

In peri-implant tissues, collagen fibers run parallel to the titanium surface, vascularity is reduced, and the barrier integrity is more susceptible to breakdown in the presence of inflammatory cell infiltration (Abrahamsson & Berglundh, 2006).

The soft tissue phenotype (thick/thin) modulates the risk of peri-implantitis and soft tissue recession; a 2024 multicenter cross-sectional study demonstrated a significantly higher prevalence of peri-implantitis in cases with a thin phenotype (Lee et al., 2024).

2.3 Measurement Techniques and Threshold Values

Various techniques are available for measuring biologic width, each with specific clinical advantages and limitations. As shown in Table 1, while traditional methods like transgingival probing offer simplicity, modern technologies such as CBCT, OCT, and intraoral scanners enable more precise and digitally integrated assessments. These approaches support improved diagnostic accuracy and personalized treatment planning.

Table 1. Comparison of Biologic Width Measurement Techniques

Measurement Approach	Clinical Application	Advantage	Limitation
Transgingival Probing / Bone Sounding	Probing under local anesthesia until bone contact is achieved; measured from the crown	Low-cost, quick	Invasive, patient discomfort, influenced by bone topography
CBCT + Digital Caliper	Virtual "bone sounding" in CBCT slices with 0.2 mm voxel resolution	Simultaneous visualization of soft and hard tissues	Radiation exposure, requires calibration
OCT (Optical Coherence Tomography)	In vivo, real-time imaging of epithelial-connective tissue interfaces using light waves	Non-invasive, high resolution	Limited access to posterior regions
Intraoral Scanner + CAD	Calculating the distance between the gingival margin and mock-up bone reference on digital STL files	Radiation-free, integrated with restorative planning	Indirect bone reference

A CBCT-based study in 2023 measured the average SCTA in the mandibular anterior region as 2.58 ± 0.34 mm, consistent with histological data (Kim et al., 2023).

OCT can identify periodontal landmarks with micron-level accuracy; its sulcus depth measurements in the anterior region are comparable to clinical probing (Jiang et al., 2023).

A CAD-based in vivo study in 2023 reported that digital scanning detected SCTA regions below 2 mm with 92% accuracy compared to invasive bone sounding (Schmidt et al., 2023).

The restorative margin of natural teeth should be placed ≥ 2.5 –3 mm coronally from the alveolar bone crest (Razi, 2019).

For dental implants, the implant platform should be positioned ≥ 3 mm apical to the planned mucosal margin to ensure adequate soft tissue thickness (Razi, 2019).

Signs of Biologic Width (SCTA) Violation: Persistent marginal erythema, bleeding on probing, increased probing depth, and radiographic evidence of crestal bone resorption (Chu et al., 2012).

To re-establish the biologic width/SCTA, both conservative (orthodontic extrusion) and surgical (flap surgery with ostectomy, crown lengthening) approaches have been standardized. In crown lengthening procedures guided by Chu's esthetic measurement indicators, an average stable SCTA of 3 mm was achieved within six months (Chu et al., 2012).

3. Etiology and Pathogenesis of Biologic Width Violation

3.1 Microbial Biofilm and Inflammation

Disruption of the biologic width (SCTA) integrity transforms the subgingival environment into an oxygen-deprived, nutrient-rich niche, thereby accelerating the formation of dysbiotic biofilms (Tanaka et al., 2023).

A 2023 review introduced the Biofilm-Mediated Inflammation and Bone Dysregulation (BIND) hypothesis, demonstrating that pathogenic microorganisms are not only initiators but also key players in sustaining alveolar bone destruction through the osteoclastogenesis–cytokine feedback loop (Tanaka et al., 2023).

The mutual exchange of nutrients and signaling molecules between periodontal pathogen-rich Gram-negative consortia (e.g., *P. gingivalis*,

T. forsythia) and opportunistic flora reinforces the chronic inflammatory microenvironment (López-Marcos et al., 2024).

The same process is observed in peri-implant tissues; however, due to differences in collagen fiber organization, the defensive capacity of the peri-implant epithelial barrier is lower, leading to a more rapid progression of peri-implantitis (López-Marcos et al., 2024).

The clinical correlation of polymicrobial synergy was confirmed in a 2024 cross-sectional study, which reported a 78% genetic overlap between bacterial communities isolated from peri-implantitis lesions and those associated with tooth-derived periodontal pathogens (López-Marcos et al., 2024).

3.2 Restorative and Iatrogenic Factors

Subgingival margins or over-contoured restorations encroaching upon the SCTA increase plaque retention, exerting chronic trauma on the epithelial-connective tissue attachment and resulting in violation characterized by bleeding or purulent exudate during invasive probing (Chen et al., 2023).

A six-month prospective follow-up study reported that while classical surgical crown lengthening achieved an average stable SCTA of 2.93 mm, the control group with biologic width violation exhibited 0.9 mm greater marginal bone resorption (Chen et al., 2023).

Digital dentistry protocols (intraoral scanning, CAD/CAM provisional restoration adjustments) were highlighted in a 2024 review to reduce biologic width violations by 35%; pre-surgical optimization of the distance between the restorative margin and bone crest can be achieved through virtual mock-ups (Smith et al., 2024).

Furthermore, conservative techniques such as biologic shaping have significantly reduced periodontal–prosthetic failure rates by preserving marginal crest levels (Rossi et al., 2024).

In implantology, the use of wide-diameter abutments without platform switching triggers microleakage and marginal bone loss in cases with soft tissue thickness < 2 mm (Huang et al., 2023).

Clinical-experimental studies have reported that gaps exceeding 60 μm at the restorative abutment interface resulted in an average of 1.2 mm bone resorption within 12 months (Huang et al., 2023).

3.3 Systemic and Behavioral Risk Factors

Nicotine-induced vasoconstriction and oxidative stress associated with cigarette smoke impair gingival microcirculation and hinder SCTA healing (Johnson et al., 2023).

A 2023 meta-analysis found that individuals with a ≥ 10 pack-year smoking history exhibited 0.56 mm greater marginal bone loss related to biologic width violation compared to non-smokers (Johnson et al., 2023).

Diabetes mellitus prolongs inflammation through hyperglycemia-induced AGE accumulation and neutrophil dysfunction; in patients with HbA1c $> 8\%$, the success rate of reattachment following surgical correction of biologic width violations decreases by 30% (Patel et al., 2022).

A 2022 cohort study demonstrated a 97% prevalence of periodontal disease in individuals with both smoking and diabetes (Patel et al., 2022).

Poor personal oral care and non-compliance with supportive periodontal therapy (SPT) doubled the rate of peri-implantitis in implant patients over a five-year follow-up (Müller et al., 2022).

Cases with keratinized mucosa < 2 mm were more prominently represented in the high-risk group (Müller et al., 2022).

Additionally, the use of antiresorptive medications (bisphosphonates, denosumab) and systemic diseases affecting host immunity (e.g., rheumatoid arthritis) are secondary factors negatively impacting SCTA stability (Müller et al., 2022).

4. Clinical Signs, Diagnosis, and Assessment

4.1 Periodontal Signs of Biologic Width (SCTA) Violation

Biologic width violation presents clinically with localized gingival erythema, hyperplasia due to chronic inflammation, bleeding on probing (BoP), persistent pocket formation (PD > 4 mm), and loss of attachment and/or marginal alveolar bone (Martínez-Canut et al., 2023).

In areas with restorative margin overstress or excessive subgingival contour, a characteristic “rubbery” edema and boggy tissue sensation during probing is observed (Rosenberg et al., 2019).

Clinical examination using bone sounding (< 2 mm SCTA) confirms the violation and guides the surgical or conservative management of the lesion (Rosenberg et al., 2019).

4.2 Peri-Implant Findings: Mucositis and Peri-Implantitis

Peri-implant mucositis is diagnosed when BoP and/or suppuration are present without radiographic bone loss exceeding 2 mm; early signs include mucosal erythema, edema, and increased probing depth ($PD \geq 4$ mm) (Berglundh et al., 2018).

In peri-implantitis, these findings are accompanied by ≥ 2 mm marginal bone resorption, crater-like radiolucencies at lesion margins, and sometimes fistula formation (Schwarz et al., 2024).

The current EFP S3 guideline recommends aggressive treatment (resective/regenerative surgery \pm antimicrobial therapy) for cases meeting all criteria of suppuration, BoP, and bone loss (Schwarz et al., 2024).

Risk modulators such as thin mucosal phenotype, non-platform switched wide abutments, and inadequate supportive care programs significantly increase the prevalence of peri-implant BoP and the rate of PD progression (Linkevicius & Puisys, 2023).

4.3 Diagnostic Methods and Measurement Protocols

Several diagnostic methods are employed to evaluate biologic width and detect early signs of peri-implant tissue breakdown. As illustrated in Table 2, while transgingival probing remains the clinical gold standard, advanced imaging techniques such as CBCT-intraoral scan superimposition and OCT offer high-resolution, non-invasive alternatives for early detection and longitudinal monitoring. These methods enhance diagnostic precision and support preventive clinical strategies.

Table 2. Diagnostic Methods for Evaluating Biologic Width and SCTA Violations

Method	Application	Diagnostic Value
Transgingival Probing / Bone Sounding	Advancing the probe to bone crest under local anesthesia and subtracting sulcus depth	Gold standard; confirms SCTA violation < 2 mm
Baseline \rightarrow Periodic Periapical / CBCT	Annual comparison using periapical (≤ 0.15 mm pixel) or CBCT (≤ 0.2 mm voxel) imaging	Bone loss ≥ 2 mm \square Peri-implantitis
CBCT + Intraoral Scan Superimposition	Digital superimposition of STL and DICOM files; automated SCTA distance calculation	$>90\%$ accuracy with radiation-free periodic scans
Optical Coherence Tomography (OCT)	Non-invasive real-time cross-sectional imaging ($8\text{--}15\text{ }\mu\text{m}$ resolution)	Detects periodontal landmarks at micron level; identifies early pocket attachment loss

Proposed Clinical Protocol:

- **Baseline Records:** Probing chart, intraoral scanning, baseline periapical or low-dose CBCT.
- **Post-healing (≤ 3 months after implant restoration):** Considered “healthy” if SCTA ≥ 3 mm and BoP negative.
- **SPT Visits (6 months–1 year):** BoP, PD, plaque index, photo-scanning. If PD ≥ 4 mm + BoP positive, confirm violation via bone sounding or CBCT.
- **OCT/Digital Overlay:** Annual in aesthetic zone cases requiring conservative monitoring.

This diagnostic algorithm supports the early diagnosis → minimally invasive intervention paradigm, thereby reducing the incidence of peri-implant and periodontal complications (Schwarz et al., 2024).

5. Biologic Width in Implantology

5.1 Implant Design and Platform Switching

In platform switching (PS) designs, the abutment diameter is narrower than the implant platform, aiming to shift the microgap region away from the bone crest, limit vertical inflammatory infiltration, and reduce coronapical SCTA remodeling (Smith et al., 2025).

A 2025 systematic review and meta-analysis (17 RCTs, ≥ 3 years follow-up) reported that marginal bone loss was 0.37 mm less in PS implants compared to platform-matched designs (Smith et al., 2025).

A 2022 multicenter RCT ($n = 120$ implants) found that after 24 months, the PS group had a mean marginal bone loss (MBL) of 0.21 ± 0.12 mm, compared to 0.62 ± 0.18 mm in the platform-matched (PM) group (Nizam et al., 2023).

Finite element analyses have shown that PS configurations reduce crestal bone stress distribution by 18–23%, minimizing the damaging effects of biomechanical loading combined with microleakage on SCTA integrity (Pessoa et al., 2022).

Practical Recommendation: Even outside the esthetic zone, PS should be preferred in cases where ≥ 2 mm peri-implant soft tissue thickness cannot be achieved, reducing marginal resorption risk by up to 30% (Smith et al., 2025). Ensuring an abutment–implant interface gap $< 40 \mu\text{m}$ reinforces long-term stability (Huang et al., 2023).

5.2 Keratinized Mucosa and Peri-Implant Soft Tissue Thickness

A keratinized mucosa (KM) width of ≥ 2 mm is critical for plaque control, patient comfort, and reducing peri-implantitis incidence (Lin et al., 2023).

A 2023 meta-analysis showed that peri-implantitis risk was 2.78 times higher in cases with $KM < 2$ mm (Lin et al., 2023).

A 2024 parallel-arm RCT demonstrated that increasing vertical soft tissue thickness (STT) from < 2 mm to ≥ 3 mm reduced crestal bone loss by 0.25 mm over one year (Thoma et al., 2024).

A 2025 RCT with 3D analysis comparing collagen matrix (VXCM) to subepithelial connective tissue graft (SCTG) found that VXCM resulted in an average thickness increase of +0.9 mm with comparable bone stability (Motta et al., 2025).

5.3 Soft Tissue Management: Grafting Techniques and Digital Planning

In a 2024 EFP JCP Digest RCT, connective tissue grafting performed during immediate implant placement showed 0.18 mm less buccal bone resorption compared to grafting delayed by three months (Cairo et al., 2024).

Soft tissue thickness (STT) augmentation around implants plays a key role in long-term peri-implant stability and esthetics. As demonstrated in Table 3, subepithelial connective tissue grafts remain the most effective approach, while less invasive alternatives like collagen matrices and pedicle flaps offer acceptable gains with reduced morbidity. Technique selection should balance clinical outcome expectations with patient-specific anatomical and procedural considerations.

Table 3. Comparison of Soft Tissue Augmentation Techniques for Peri-Implant Sites

Technique	Average STT Gain	Advantage	Disadvantage
Subepithelial Connective Tissue Graft (SCTG)	+1.1 mm	“Gold standard”; high success rate	Donor site morbidity
Collagen Matrix (VXCM)	+0.9 mm	No donor site; low morbidity	Slight volume loss
Pedicle Mucosal Flap	+0.7 mm	Maintains vascular continuity; excellent esthetic integration	Technically demanding

Digitally guided surgery (intraoral scanner + CBCT superimposition) allows for virtual preoperative assessment of soft tissue thickness and keratinized mucosa (KM) width, enabling objective evaluation of grafting needs and facilitating patient-specific planning of platform switching and abutment configurations (Nicoli et al., 2024).

Clinical Algorithm:

- **Preoperative Digital Analysis:** Indication for grafting if KM < 2 mm and/or STT < 2 mm.
- **Immediate Implant + PS + Graft:** Provides optimal SCTA stability.
- **Supportive Periodontal Therapy (SPT):** Every 3–4 months in the first year, then every 6 months with digital scanning/probing.

6. Treatment and Prevention Strategies

6.1 Conservative Periodontal Treatment

6.1.1 Subgingival Disinfection and Biofilm Control

In early stages of SCTA violation, systematic subgingival curettage, root planing with ultrasonic instruments, and 0.12% chlorhexidine irrigation protocols significantly reduce the inflammatory burden (Lee et al., 2023).

Three-month follow-ups have reported an average reduction of 1 mm in BoP and PD values following these interventions (Lee et al., 2023).

Adenosine triphosphate (ATP) biofilm tests provide quantitative chairside detection of residual bacteria, making them valuable monitoring tools, especially in high-risk patients (e.g., smokers, diabetics) (Shah et al., 2022).

6.1.2 “Biologic Shaping” (BS)

Rather than surgically repositioning the marginal gingiva apically, BS involves recontouring the preparation margin to be supracrestal relative to the cemento-enamel junction (Rossi & Cortellini, 2024).

This technique achieved an average SCTA preservation of 2.1 mm in a 12-month prospective study and reduced postoperative sensitivity by 40% compared to conventional crown lengthening (Rossi & Cortellini, 2024).

6.1.3 Orthodontic Extrusion

Gradual extrusion of teeth (≈ 1 mm/month) through orthodontic forces allows coronal relocation of the SCTA in parallel with bone remodeling (Hernandez et al., 2023).

A multicenter 2023 study reported achieving an average of 3 mm of healthy SCTA up to the restorative margin following orthodontic extrusion (Hernandez et al., 2023).

6.2 Surgical Approaches

6.2.1 Crown Lengthening (Gingivectomy, Apically Positioned Flap + Ostectomy)

A randomized controlled 6-month follow-up study showed that apically positioned flap + ostectomy resulted in 0.4 mm more stable SCTA compared to gingivectomy (Ahmed et al., 2022).

Additionally, a transient coronal rebound of the gingival margin by approximately 1.2 mm was observed during the early healing phase (Müller & König, 2021).

6.2.2 Regenerative Surgery (GTR / GBR)

In periodontal intraosseous defects, guided tissue regeneration (GTR) supported by ePTFE membranes or CAD/CAM titanium meshes achieved an average clinical attachment level (CAL) gain of 4.3 mm over five years (Stavropoulos et al., 2023; Kim et al., 2021).

In peri-implant cases with hard tissue loss, a combined protocol of conical implants + platform switching + guided bone regeneration (GBR) limited crestal bone loss to just 0.26 mm after 24 months (White et al., 2023).

6.2.3 Resective/Regenerative Protocols for Peri-Implantitis

The 2024 EFP peri-implant disease guidelines recommend resective decontamination combined with apically positioned flap for bone loss ≤ 5 mm (Schwarz et al., 2024).

For deep crater-like defects, a combined regenerative protocol involving titanium curettes, Er:YAG laser detoxification, and particulate bone grafting is advised (Matarasso et al., 2023; Kang & Park, 2022).

6.3 Restorative Redesign and Material Selection

6.3.1 Supracrestal Margin Design

With CAD/CAM digital wax-ups, the distance of restorative margins from the bone crest can be adjusted to ≥ 2.5 mm during the simulation phase, reducing iatrogenic violations by 35% (Barone et al., 2023).

Minimal invasive preparations guided by digital mock-ups ensure contours compatible with SCTA in both tooth- and implant-supported restorations (Barone et al., 2023).

6.3.2 Biomimetic Materials

Zirconia or high-strength lithium disilicate ceramic abutments reduce plaque accumulation and peri-implant BoP rates compared to metal abutments (Zembic et al., 2022).

In 36-month cohort data, peri-implantitis incidence was 3.1% in zirconia abutment cases versus 8.4% in titanium abutment groups (Zembic et al., 2022).

6.3.3 Microgap Management

Platform-switched interfaces with machining tolerances of 20–40 μm significantly limit marginal bone loss (Huang et al., 2023).

Gaps beyond this threshold facilitate anaerobic leakage and inflammation, initiating crestal resorption as early as three months post-restoration (Huang et al., 2023).

6.4 Supportive Care Protocols (SPT)

6.4.1 Risk-Based Personalization

According to EFP (European Federation of Periodontology) and BSP (British Society of Periodontology and Implant Dentistry) guidelines, patients with good oral hygiene and < 6 cigarettes/day are recommended SPT every 6 months, while high-risk individuals (smoking > 10 pack-years, HbA1c $> 8\%$) require 3–4-month intervals (Herrera et al., 2024; Roccuzzo & Layton, 2022).

6.4.2 Professional Deplaquing and Low-Energy Laser

The combination of erythritol-glycine air polishing and low-energy diode laser effectively removes plaque biofilm without damaging titanium surfaces (Clerc et al., 2023).

An 18-month follow-up demonstrated control of peri-implant PD progression below 0.3 mm with this protocol (Clerc et al., 2023).

6.4.3 Patient Education and Home Care

The combined use of oral irrigators and interdental brushes reduces plaque index by 22% and peri-implant BoP by 18% compared to brushing alone (Chapple et al., 2022).

Motivational interviewing techniques are recommended to ensure behavioral change sustainability (Chapple et al., 2022).

7. Future Perspectives and Innovative Approaches

7.1 Bioengineering and Regenerative Biology

Current research in regenerating lost hard and soft tissues in the periodontal-peri-implant complex focuses on smart biomaterials and 3D bioprinting technologies (Chen et al., 2025).

Multilayered, growth factor-loaded hydrogels enable simultaneous stimulation of angiogenesis and osteogenesis cascades at the bone-connective tissue interface through controlled release (Chen et al., 2025).

A recent review reported that 3D bioprinted scaffolds with cell inclusions successfully mimicked periodontal ligament-specific collagen orientation, achieving dentoalveolar integration in vivo within 12 weeks (Lopez-Heredia et al., 2025).

Functionality-based evaluation standards (mechanical properties, vascularity, cell-matrix integration) are now being added to traditional histomorphometry in assessing regenerative success (Academy of Dental Materials, 2024).

The Academy of Dental Materials has detailed clinical translatability criteria for biomimetic scaffolding, aiming for standardized protocols in future clinical applications (Academy of Dental Materials, 2024).

7.2 Digital Technology, Artificial Intelligence, and Optical Diagnostics

Optical Coherence Tomography (OCT) enables non-invasive, micron-resolution mapping of the periodontal sulcus and peri-implant soft tissues (Jafer et al., 2023).

A 2023 retrospective study confirmed a 93% concordance between sulcus depth measurements via OCT and clinical probing, supporting its diagnostic accuracy (Jafer et al., 2023).

The integration of OCT datasets with deep learning algorithms aims to predict biologic width violations before clinical symptoms manifest (Wang et al., 2024).

Artificial intelligence (AI) models for automatic detection of marginal bone loss on radiographs have shown an average accuracy of 84% in current meta-analyses (Mohanty et al., 2025).

However, adaptation to data heterogeneity and ethnic soft tissue variations remains a challenge in widespread clinical adoption (Mohanty et al., 2025).

Clinical decision support systems incorporating patient-specific risk factors (smoking, diabetes, bone phenotype) have demonstrated the ability to predict peri-implantitis development 3–5 years in advance, as reported in a 2022 machine learning pilot study (Koo et al., 2022).

Digital workflows also facilitate real-time marking of SCTA safety zones in surgical guide designs through intraoral scanning + CBCT superimposition, enabling personalized simulation of grafting needs, implant platform levels, and platform switching configurations (Nicoli et al., 2024).

7.3 Long-Term Clinical Research and Standardization

While current RCTs mainly report ≤ 3 -year outcomes, monitoring biologic width stability over ≥ 10 years is crucial for understanding long-term oral-systemic impacts (e.g., cardiometabolic inflammation) (IDEALD Consortium, 2025).

Global consensus is needed to define standardized terminology (SCTA vs biologic width), measurement protocols (OCT ≥ 100 kHz scanning, CBCT ≤ 0.2 mm voxel), and risk-stratified study designs (IDEALD Consortium, 2025).

The multicenter IDEALD Phase 2 cohort initiated in 2025 aims to provide the first adequately powered 15-year dataset comparing platform-switched and platform-matched implants (IDEALD Consortium, 2025).

8. Conclusion

The preservation of biologic width is indispensable for maintaining periodontal and peri-implant health (Pini Prato & Baldi, 2021).

From historical conceptualization to measurement techniques, etiology of violations, and multidisciplinary treatment protocols, current evidence supports the immunological barrier function of $\geq 2\text{--}3$ mm supracrestal tissue attachment (Roccuzzo et al., 2024).

Platform-switching implant designs, thick keratinized soft tissue grafts, and digitally guided restorative planning have significantly reduced iatrogenic biologic width violations (Roccuzzo et al., 2024).

In the future, regenerative materials supported by 3D bioprinting and AI-based risk modeling will form the foundation of personalized preventive and therapeutic strategies (Zhang et al., 2025).

Long-term, standardized clinical studies will elucidate the real-world impact of these innovations and validate their potential to reduce the global burden of periodontal and peri-implant diseases (Zhang et al., 2025).

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Implant-Supported Fixed Protheses

Gizem Erdaş¹

Abstract

Implant-supported fixed restorations have become a widely accepted treatment modality in contemporary prosthodontics, offering functional and esthetic solutions for partially and fully edentulous patients. Two main retention methods—screw-retained and cement-retained restorations—are commonly used, each presenting specific clinical advantages and limitations. Screw-retained prostheses allow retrievability and reduce the risk of peri-implant inflammation due to excess cement, while cement-retained options often offer superior esthetics and occlusal control. The choice between these techniques depends on various factors including implant angulation, interocclusal space, esthetic demands, and maintenance considerations. This text provides a comparative overview of both systems, highlights indications and contraindications, and discusses current materials, design principles, and long-term outcomes based on clinical experience and literature.

Overview of Implantology

According to its literal definition, an implant is an organic or inorganic substance that is inserted between living tissues to restore a function that has been lost. Branemark introduced us to the fundamental idea of oral implantology in dentistry, known as osseointegration, in 1952. He published the first osseointegrated implant cases in 1969. Numerous implant designs have been created since then, and the idea of osseointegration has advanced. Alongside these advancements, implant-supported prostheses have evolved and are now widely used in contemporary dentistry with good success rates. The prosthetic restoration phase begins either without waiting for the osseointegration process of implants to be finished or after it is finished. The measurement step is the initial stage of prosthetic repair.

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1. Impression Technique

Impression copings, also known as impression posts, enable the accurate transfer of implant placements from the jawbone to the working model. These components ensure accurate transfer of implant positioning and facilitate passive compatibility of the implant prosthesis, provided that the appropriate impression technique is employed. Impression posts are non-standard. Each manufacturer may possess a distinct imprint post for every implant style. There are three types: open tray impression post, closed tray impression post (transfer type impression), and digital scan body. This categorization can also be differentiated based on the designs of implant manufacturers. For instance, there exist shorter impression posts for application in the posterior region, as well as larger or narrower impression posts according to the preferred gingival emergence profile. Indexed impression posts are intended for single-unit restorations, whilst non-indexed impression posts are utilized for multi-unit restorations.

Short copings and short keys have been developed specifically for obtaining posterior arch measurements in patients with restricted mouth opening.

Impression procedures must be accurately selected based on the specific circumstance. Nonetheless, it must be acknowledged that there is no singular truth. Multiple impression techniques may be appropriate for a given scenario.

Impression methodologies encompass open tray impressions, closed tray impressions, press-fit impressions, and intraoral scanning. The press-fit technique is seldom favored due to its limited precision. Implant-supported restorations are classified into two primary categories: screw-retained and cement-retained. Each possesses distinct limitations and advantages. Aggregated data from clinical investigations indicate 5-year survival rates of 96.03% for cement-retained restorations and 95.55% for screw-retained reconstructions. (Buser et al., 2012)

Both retention techniques have been utilized for single, multiple, and cross-arch fixed dental prostheses. Long-span prosthesis should ideally be screw-retained for enhanced maintenance efficiency. The literature indicates that long-span restorations are associated with an increased risk of problems. (Salvi & Bragger, 2009)

This should also pertain to cantilevered FDP designs, as these prostheses require increased care and servicing. (Aglietta et al., 2009; Shadid & Sadaqa, 2012)

It might also be easier to achieve sufficient retention for compensation of the leverage of the extension.

Nevertheless, if the implant is not positioned in a prosthetically optimal location, with the future access hole of the intended crown situated below the planned incisal edge, cement retention frequently becomes the sole treatment alternative. Consequently, meticulous treatment planning and prosthetically guided implant placement must be obligatory for implant therapy. (Wittneben & Weber, 2012) The clinician is required to make a decision that is based on the specific case, taking into account the benefits and drawbacks of cement-retained and screw-held restorations. The requisite decision tree for this is presented in Fig.1

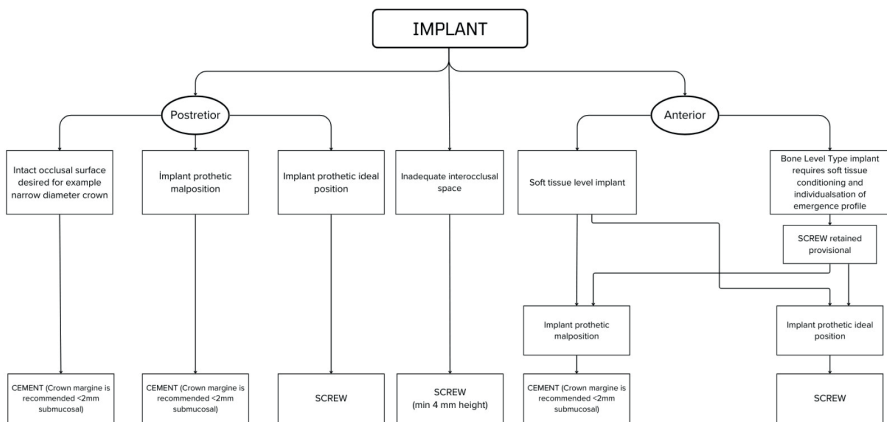


Figure 1. Decision tree for implant-supported prostheses.¹¹

2.Screw-Retained Restorations

Screw-retained implant-supported prostheses were originally utilized at the inception of implants, particularly for full-arch prosthesis in edentulous patients following the ‘ad modum Branemark’ procedure.

This restoration involves an implant abutment and an implant-supported crown that are integrated as a single unit, with the implant and crown secured together by screws. Currently, cement-retained restorations have mostly been supplanted by screw-retained restorations. The lack of cement offers a benefit regarding peri-implant health. Screw-retained restorations necessitate a minimum interocclusal distance. They are more easily removed

than cement-retained restorations when maintenance, hygiene, or surgical treatments necessitate their removal. (Chee & Jivraj, 2006)

The drawbacks of screw-retained prostheses include extended manufacture time and expense for bridge-designed prosthetics, as well as the presence of a screw hole in the occlusal table, complicating occlusal adjustments in the posterior regions. In the anterior region, access to the screw does not significantly influence occlusion; thus, it is unnecessary to restrict screw access for this reason. Research has demonstrated that the chipping rate in screw-retained restorations exceeds that of cement-retained restorations. Screw-retained restorations are preferable in cases of insufficient interocclusal distance, cantilever extensions, extensive edentulous spans, when minimizing the risk of cement residue in the aesthetic zone is desired, and when gingival shaping will be performed with temporary prostheses.

3.Cement-Retained Restorations

The primary benefits of cement-retained restorations include enhanced passive adaptation due to the cement gap between the implant abutment and the restoration, accommodation for misaligned implants, removal of screw access holes in teeth with limited occlusal surfaces, and simplified occlusion in narrow-diameter restorations in the posterior area. Moreover, cement-retained prostheses are more economical than screw-retained alternatives.

The primary drawback is the challenge of eliminating surplus cement that leads to peri-implantitis or peri-implant mucositis. (Linkevicius et al., 2013; Ramer et al., 2014; Linkevicius et al., 2013)

A further drawback of cemented implant-supported restorations is the potential for cementation mistakes. If the prosthesis is improperly positioned and the cement solidifies incorrectly, the prosthesis must be extracted. This may result in the fracture of the prosthesis and harm to the implant or implant spacers.

In addition, if these prostheses need to be removed in any case, they are quite difficult to remove compared to screw-retained prostheses and include the risks mentioned above.

Another risk factor is the occurrence of screw loosening in the absence of decementation. The prosthesis must be detached from the intermediate implant component (abutment), after which the abutment screw should be torqued, and the prosthesis re-cemented, a task that is improbable to accomplish. The prosthesis may be inseparable from the abutment and may require cutting for removal. Cemented restorations may experience loss of

retention and subsequently decement due to microleakage. This poses the risk of aspiration or ingestion by the patient.

Mechanical considerations influence retention in cement-retained implant-supported prostheses. The retention of the prosthesis is influenced by factors like length, diameter, surface roughness, taper angle, number of abutments, position of the abutments inside the dental arch, and the type of cement used. In the fabrication of a fixed cement-retained restoration, a specific cement gap must be maintained between the implant abutment and the internal surface of the prosthesis. The gap can be modified with spacers or digitally within CAD/CAM software. The retention of cement-retained implant-supported restorations, characterized by adequate interocclusal distance and a 6-degree taper angle for optimal cement gap, is 3 to 4 times superior to that of fixed restorations on natural teeth. (Millen et al., 2015)

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Implant-Supported Removable Protheses

Başak Topdağı¹

Abstract

Despite advances in preventive dentistry, tooth loss remains a significant concern, affecting oral and overall health. It leads to functional, aesthetic, and psychological challenges, impacting the quality of life. Major contributing factors include periodontal diseases, age, socioeconomic status, and poor oral hygiene. Partial edentulism, particularly free-end cases in posterior regions, is commonly treated with removable dentures, which, over time, accelerate bone loss and compromise prosthesis stability.

Implant-supported prostheses offer superior stability, function, and bone preservation compared to traditional removable dentures. In fully edentulous patients, the most common approach involves two implant-supported overdentures in the mandible, while at least four implants are recommended for the maxilla. Treatment planning should consider bone volume, patient expectations, and biomechanical requirements. Implant-supported prostheses help maintain occlusal balance, enhance chewing efficiency, and improve overall well-being.

Long-term implant success depends on proper maintenance and periodic follow-ups. Immediate loading protocols provide faster rehabilitation but require optimal primary stability. Additionally, occlusal considerations and prosthetic design play crucial roles in ensuring longevity and function. The increasing global demand for implant treatments highlights the need for comprehensive planning and patient education to prevent progressive bone loss and improve oral rehabilitation outcomes.

1. Implant-supported prosthesis requirement

Despite advancements in preventive dentistry, the prevalence of tooth loss continues to rise. Oral health plays a crucial role in overall well-being and is closely linked to quality of life. While general health was once considered

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the primary factor affecting quality of life, the significance of oral health in this regard has gained increasing recognition over time.(Oyar et al., 2019)

Tooth loss is a key indicator of oral health and is influenced by various factors, including age, gender, oral hygiene habits, socioeconomic status, excessive chewing forces, gingivitis, and periodontitis. Missing teeth can lead to functional impairments, speech difficulties, and aesthetic concerns, all of which negatively impact both oral and overall health. Therefore, addressing tooth loss through appropriate treatment is essential.(Guan et al., 2025)

According to the World Health Organization, an adult requires at least 21 functional teeth to maintain proper oral function.(Oyar et al., 2019)

The prevalence of partial edentulism is a growing concern, as the number of implants used to restore these cases continues to rise. The transition from having a full set of natural teeth to partial tooth loss is most prominent among individuals aged 35 to 54. This age group is experiencing a population increase of 30%, outpacing all other demographics. As a result, this shift is expected to lead to a significant rise in the demand for dental implant treatments in the coming years.(Chen et al., 2024) It is estimated that approximately 812 million people worldwide are potential candidates for dental implants. Tooth loss becomes increasingly prevalent with age, affecting different demographics at varying rates. Among individuals aged 25 to 44, around 120 million experience partial edentulism, while the number rises to 156 million in the 45 to 54 age group. The prevalence continues to increase in older populations, with approximately 200 million people aged 55 to 64 requiring implants. In the 65 and older category, the highest number of cases is observed, with 336 million individuals affected. These estimates highlight the growing need for implant treatments globally, though factors such as socioeconomic status, oral hygiene habits, and access to dental care influence the actual demand.(Bongaarts, 2020; Douglass & Watson, 2002)

Molars are the most frequently lost teeth, and the occurrence of partial free-end edentulism is particularly concerning, as it is commonly managed with removable dentures. While this condition is rarely seen in individuals under 25, its prevalence increases with age. The mandible is more frequently affected than the maxilla across all age groups. Among younger individuals aged 25 to 44, unilateral free-end edentulism is more prevalent than bilateral cases, impacting approximately 13.5 million people. (Karadi et al., 2024) By the ages of 45 to 54, about 31.3% of individuals experience mandibular free-end edentulism, whereas 13.6% have maxillary involvement, affecting nearly 9.9 million people. The condition worsens significantly in individuals

aged 55 to 64, with 35% of mandibular and 18% of maxillary arches being edentulous, making around 11 million people potential candidates for dental implants.(Al-Rafce, 2020)

2. Anatomical Changes Caused by Edentulism

Tooth loss leads to significant deformations, particularly in the alveolar bone structures. In this context, basal bone and alveolar bone exhibit different behaviors due to their distinct embryological origins. While the development of basal bone in the fetus occurs independently of dental bud formation, alveolar bone development begins with the formation of the epithelial tissue of the dental buds. Essentially, this phenomenon is the primary reason for the lifelong physiological dependency between alveolar bone and dental tissues.(Chen et al., 2010)

Additionally, according to Wolff's law, bone continuously remodels itself in response to the mechanical forces it is subjected to. The shape of the bone is influenced by abnormal loads or functional losses in the surrounding tissues. The morphology and density of the bone rely on mechanical stimulation to maintain their physiological integrity.(Frost, 2004) Teeth transmit pressure and tensile forces to the surrounding structures through their periodontal tissues. This process generates a piezoelectric effect in the inorganic component of the bone. When a tooth is lost, the absence of mechanical stimulation leads to the atrophy of the alveolar bone. Research indicates that within the first year following tooth loss, bone width decreases by approximately 25%, while height loss reaches around 4 mm during the same period.(Jung et al., 1996)

Although the mandible initially has twice the bone height of the maxilla, long-term edentulism results in significant maxillary bone loss as well. Alveolar bone development requires the presence of teeth, and continuous stimulation is necessary to maintain its density and volume.(Moldovan et al., 2018) However, removable dentures whether complete or partial fail to provide this stimulation and instead accelerate bone loss. Unlike natural teeth, which transmit masticatory forces throughout the bone, removable prostheses transfer force only to the bone surface, leading to reduced blood supply and total bone volume loss.(Wyatt, 1998)

This issue has long been observed but not adequately addressed by traditional dentistry. Many doctors fail to recognize or educate patients about the progressive bone loss that follows tooth extraction(D'Addazio et al., 2021). Furthermore, patients are often unaware of the anatomical changes and long-term consequences of continued bone resorption. The

problem worsens when patients wear poorly fitting soft tissue-borne prostheses, which further accelerate bone loss. Many patients only seek dental evaluation after years, when their dentures have become uncomfortable or no longer functional. Thus, traditional tooth replacement methods frequently contribute to bone loss in ways that are not adequately considered by either doctors or patients. (Müller et al., 2013)

One of the first consequences of bone loss is a decrease in bone width, which can lead to discomfort when a thin residual ridge is subjected to pressure from a removable prosthesis. Continued mandibular atrophy eventually results in prominent mylohyoid and internal oblique ridges covered by thin, mobile, and unattached mucosa, further complicating prosthetic treatment. (Kuć et al., 2017) Completely edentulous patients, bone loss leads to several significant consequences. One of the primary effects is the reduction in both the width and height of the supporting bone. As bone resorption progresses, the prominence of the mylohyoid and internal oblique ridges increases, often resulting in painful pressure points. Additionally, there is a gradual decrease in the surface area of keratinized mucosa, which further compromises oral comfort and stability. (Lee & Saponaro, 2019) As superior genial tubercles become more pronounced, painful spots develop, contributing to increased denture mobility. Muscle attachments shift closer to the crest of the ridge, leading to greater instability of the prosthesis. The contraction of the mylohyoid and buccinator muscles can cause the denture to lift, affecting posterior support. Furthermore, due to anatomical inclinations, significant bone loss alters mandibular angulation, resulting in anterior displacement of the denture. (D. Mericske-Stern et al., 2000)

3. Decreased effectiveness of removable prostheses over time

A person with natural teeth can apply an average force of 150 to 250 psi in the first molar region during occlusal movements. This force can increase up to 1000 psi during parafunctional activities. However, in edentulous patients, the maximum occlusal force drops below 50 psi. As the duration of edentulism increases, the force they can exert gradually decreases over time, negatively affecting prosthesis stability. Many patients using traditional removable dentures are unable to consume a variety of foods.. (Singhal et al., 2022) Poor chewing performance in edentulous patients can lead to digestive issues and impaired nutrient absorption. Studies show that inadequate dental function affects swallowing, increases disease risk, and may shorten lifespan. Oral health is closely linked to overall well-being, with dental disorders associated with cardiovascular diseases. Restoring proper

function in the stomatognathic system can enhance both quality of life and longevity.(Suganthi, 2018)

The use of removable partial dentures has been associated with various negative effects. Studies indicate a four-year survival rate of 60% and a ten-year survival rate of 35% for these prostheses. Over time, abutment teeth require increasing maintenance, with 60% needing repairs within five years and 80% within ten years. Additionally, patients experience greater mobility in abutment teeth, along with increased plaque accumulation, bleeding on probing, and a higher risk of caries.(Preshaw et al., 2011) Bone loss in edentulous areas progresses more rapidly due to removable prosthesis use. Research has shown that 44% of abutment teeth are lost within ten years. Given these challenges, alternative treatment options that help preserve oral health and prevent bone loss are often preferred.(Wöstmann et al., 2005)

4.Advantages of Implant-Supported Prostheses

Prostheses designed with support from implant abutments offer numerous advantages compared to traditional restorations. The primary benefit is the preservation of bone integrity and physiological continuity, as implants placed within the alveolar bone help distribute stress and load, preventing their harmful effects.

Additionally, implant-supported prostheses provide superior stability compared to removable dentures, help maintain vertical dimension, and contribute to the stabilization of occlusion. They also enhance proprioception, allowing for better sensory feedback, and significantly improve chewing efficiency. Furthermore, these restorations have greater longevity, ultimately leading to better nutrition and an improved quality of life.(Doundoulakis et al., 2003)

5.Treatment planning in implant dentistry

Implant dentistry offers highly personalized treatment plans compared to traditional prosthetic treatments. Edentulous patients seek not implants themselves but the restoration of their missing teeth. While past approaches focused primarily on bone support for implant placement, modern treatment planning prioritizes prosthetic design first. However, several additional factors influence prosthesis design. One of the fundamental principles of implant treatment is to provide the most predictable and cost-effective solution that meets both the patient's anatomical needs and personal expectations. For fully edentulous patients, removable implant-supported prostheses offer several advantages over fixed restorations. Some of the advantages of

removable implant-supported restorations include; include improved facial aesthetics, the ability to be removed at night, fewer implant requirements, lower cost, easier long-term complication management, and simpler hygiene procedures.(Tischler, 2010) However, some fully edentulous patients may require fixed prostheses due to either personal preference or their existing oral condition. For instance, if a patient has sufficient bone volume and implants have already been placed, inadequate interarch space may make a removable prosthesis unfeasible. Currently, most treatment plans for fully edentulous patients involve a maxillary complete denture (palatal prosthesis) combined with a mandibular overdenture supported by two implants. However, this approach may not be suitable for all patients, as maxillary bone resorption continues over time, and the long-term consequences of bone loss should be carefully considered. However, in partially edentulous patients, implant-supported fixed bridges are often the best solution. The psychological and functional advantages of fixed prostheses make them a preferred option. The ideal treatment plan should be tailored to the patient’s existing anatomical condition and personal expectations.(Misch, 2007; Stanford, 2005)

Carl Misch defined five fundamental prosthetic options in implant dentistry in 1989.(Misch, 1989)(Table 1)

Table 1. Carl Misch's 1989 classification of prosthetic options in implant dentistry

Type	Definition
FP-1	A fixed prosthesis replaces only the crown (the upper part of the tooth) and appears just like a natural tooth.
FP-2	A fixed prosthesis replaces the crown and part of the root; while it appears normal on the occlusal (chewing) surface, it may have an elongated or prominent contour at the gingival level.
FP-3	A fixed prosthesis replaces the crowns of missing teeth, the gingival color, and part of the edentulous area. It typically includes acrylic gingiva and prosthetic teeth, but it can also be made of porcelain-metal.
RP-4	A removable prosthesis is a fully implant-supported overdenture.
RP-5	A removable prosthesis is an overdenture supported by both implants and soft tissue.

In 1989, Carl Misch defined five fundamental prosthetic options in implant dentistry. The first three options (FP-1, FP-2, FP-3) are fixed prostheses, while the last two (RP-4, RP-5) are removable prostheses. They are classified based on the amount of implant support rather than appearance. RP-4 is fully supported by implants, whereas RP-5 is supported by both implants and soft tissue.(Misch, 1989)

6.Removable Prostheses

Removable prosthetic options primarily consist of overdenture prostheses, which are classified into two main categories: fully implant-supported prostheses (RP-4) and prostheses supported by both implants and soft tissue (RP-5).(Taylor et al., 2005)

6.1.RP-4 Overdenture

This type of prosthesis is entirely supported by implants or natural teeth and provides a rigid (fixed and secure) structure when placed. A superstructure, which connects the prosthesis to the overdenture attachments, integrates the tissue bar or implant abutments into a unified system. Generally, 5-6 implants are required for the mandible and 6-8 implants for the maxilla. In removable prostheses, teeth and acrylic volume are larger, requiring implants to be positioned more lingually and deeper. In addition to implant abutments, a superstructure and overdenture attachments must be included. (Misch, 2008)

6.2.RP-5 Overdenture

RP-5 is a removable prosthesis that combines implant support with soft tissue support, resembling traditional overdenture prostheses. A fully edentulous mandibular overdenture can be supported in different ways:

1. Two independent implants in the anterior region or connected implants in the canine area → Enhances retention.
2. Three implants placed in the premolar and central incisor regions → Provides lateral stability.
3. Four implants with a bar attachment → Offers greater stability and reduces the need for soft tissue support.(Hegde, 2024)

6.2.1.Bone Resorption in RP-5 Prostheses

Since RP-5 overdentures are not fully supported by implants, alveolar bone resorption continues in soft tissue-supported areas. As a result, periodic adjustments, including relining and occlusal modifications, are necessary every few years. Bone loss in RP-5 prostheses can be two to three times greater than in conventional complete dentures.(Gowd et al., 2017)

7.Partially Edentulous Arches

Several classification systems have been proposed for partially edentulous arches, primarily to aid visualization of hard and soft tissue relationships and

facilitate communication. The Kennedy Classification is the most widely used system in clinical practice today, categorizing edentulism into four main classes:

Class I: Bilateral edentulism in the posterior region.

Class II: Unilateral edentulism in the posterior region.

Class III: A bounded edentulous space within the dental arch.

Class IV: Anterior edentulism crossing the midline. (Kuzmanovic et al., 2004)

To enhance the practical application of this system, Applegate's eight rules were introduced:

- Classification should only include natural teeth involved in the final prosthesis.
- If a tooth is planned for extraction, classification is determined based on the post-extraction condition.
- If second or third molars are not part of the restoration, they are not considered in classification.
- The most posterior edentulous area dictates the classification.

Additional edentulous areas are considered modifications and are numbered rather than measured by extent. (Kuzmanovic et al., 2004)

8. Implant Treatment Planning: Division of the Fully Edentulous Jaw

In implant treatment planning, a fully edentulous jaw is divided into specific regions. According to the Misch-Judy Classification, each region (anterior, right posterior, left posterior) is evaluated independently. Therefore, a single jaw may have one, two, or three different bone volume classifications. (Misch, 1999)

Mandible (Lower Jaw):

- Right and left posterior regions: Extend from the mental foramen to the retromolar pad.
- Anterior region: Located between the mental foramina, typically extending from premolar to premolar.

Maxilla (Upper Jaw):

- Right and left posterior regions: Typically begin in the second premolar region and are defined by maxillary sinus bone height.
- Anterior region: Located between the first premolars, positioned in front of the maxillary sinus.

Type 1: Fully Edentulous Jaw with Similar Bone Volume in All Three Regions

- When all regions have similar bone volume, the jaw is classified as Type 1.
- Type 1 is further divided into four subcategories.

Type 1, Division A: Abundant Bone Volume

- All regions contain a sufficient amount of bone volume.
- The desired number of root-form implants can be placed.
- Fully implant-supported fixed prostheses are possible.

Type 1, Division B: Sufficient but Narrow Bone Volume

- All regions have a sufficient but narrow bone volume.
- Narrow-diameter root-form implants can be used.
- In the anterior region, osteoplasty can be performed to increase bone width.
- However, if posterior bone height cannot be increased, smaller diameter implants are typically placed.

Type 1, Division C-w: Insufficient Bone Width

- Bone width is inadequate for implant placement.
- If the patient desires a removable implant-supported prosthesis, osteoplasty can convert it to C-h form.
- For a fixed prosthesis, an autogenous bone graft is required.

Type 1, Division C-h: Insufficient Bone Height

- There is not enough bone for long-term fixed implant-supported prostheses.
- Removable implant-supported prostheses (RP-4, RP-5) are generally recommended.

- The anterior region of the mandible can be treated with full subperiosteal implants.
- In some cases, root-form implants in the anterior region may support an RP-5 prosthesis.

Type 1, Division D: Severe Bone Loss

- This represents the most complex cases, where autogenous bone grafting (iliac crest) may be required.
- After six months, a total of 6-10 implants can be placed in the anterior and posterior regions.

Type 2: Different Bone Volume in the Anterior and Posterior Regions

In these cases, posterior bone volume is generally lower than in the anterior region. The classification is written with the anterior region first, as it plays the most critical role in treatment planning.

Type 2, Division A, B (Anterior A, Posterior B)

- The anterior region has abundant bone volume, while the posterior region is narrow.
- Narrow-diameter implants or bone augmentation may be considered for the posterior region.

Type 2, Division A, C (Anterior A, Posterior C)

- Abundant bone is present in the anterior region, while severe bone loss is seen in the posterior region.
- In the mandible, implants are typically placed only in the anterior region.
- In the maxilla, sinus grafting can be used to support the posterior region.
- In cases of severe posterior bone loss, the augmentation process may be prolonged. (Misch & Resnik, 2020)

9. Advantages of Implant-Supported Overdenture Prostheses Compared to Fixed Prostheses

- Since the support area is not limited to the implants, fewer implants are required.
- When there is insufficient bone, the need for bone grafting is reduced.

- Provides greater flexibility in treatment planning during implant placement.
- The soft tissue support helps restore lost facial profile support more easily.
- The positioning of the teeth on the designed prosthesis can be arranged more freely.
- Requires less technical precision during production and planning.
- Periodic implant check-ups are easier.
- Hygiene procedures are more convenient to perform.
- In patients with parafunctional habits, the ability to remove the prosthesis when necessary is an advantage.
- Repairs are much easier compared to fixed prostheses.

More cost-effective, and a fixed prosthesis can be planned in the future if needed. (Prithviraj et al., 2014)

10. Disadvantages of Implant-Supported Overdenture Prostheses

- Psychological motivation may decrease in patients who expect to use a fixed prosthesis.
- A sufficient interarch space (12–15 mm) is required.
- The intermediate connection units may need to be replaced over time.
- Since the structural components of the prosthesis are made of acrylic, repairs may be required over time.
- Due to tissue changes, the free-ending parts may require relining over time.
- Bone resorption in the posterior region can be up to three times faster in RP-5 prostheses; therefore, these prostheses should be considered temporary, and patient education should be provided accordingly.

Food retention issues. (Gray & Patel, 2021)

11. Overdenture Movement and Related Complications

The most common complications encountered in mandibular overdenture prostheses arise due to an insufficient understanding of the principles of retention, support, and stability.

Precision attachments used in overdenture prostheses have different ranges of motion (ranging from minimal movement to being relatively stable). The mobility of an overdenture varies depending on the type of attachment used and the number of existing implants. In nearly fixed prostheses, the load dynamics should resemble those of fixed prosthetic restorations. (Sadowsky, 2007)

12. Overdenture Movement Classification (PM - Prosthesis Movement)

This classification evaluates the general movement directions of the prosthesis, independent of the movement directions of the attachment components. The primary aim is to determine how much the prosthesis moves during function.

PM-0 (Non-Movable Prosthesis)

- Although the prosthesis is removable, it does not move during function.
- It is fully implant-supported and should be planned like a fixed prosthesis.

PM-2 (Movement in Two Directions - Hinge Motion)

- The prosthesis moves like a hinge (e.g., only up-down or front-back movement).
- Hader bar and Dolder bar hinge attachments are used.
- More movement may be observed, especially in the posterior regions.

PM-3 (Movement in Three Directions - Apical and Hinge Motion)

The prosthesis can move both apically (vertically) and in a hinge motion. When a Dolder bar or Hader bar is used with some space, this movement may be desirable if the ridge anatomy is weak.

PM-4 (Movement in Four Directions)

PM-5 (Multidirectional Movement)

- The prosthesis moves in multiple directions.
- Typically seen in soft tissue-supported prostheses.
- Found in types with magnetic attachments.

PM-6 (Movement in All Directions)

- The prosthesis moves completely freely.

- Implants must remain independent.
- Frequently observed in O-ring or ERA-type attachments.

Common in RP-5 prostheses.(Richter, 1989)

13.Mandibular Implant Site Selection

The mandibular anterior region is divided into five equal vertical sections, and implant placement sites (potential areas) are labeled from right to left as A, B, C, D, and E. In mandibular implant placement, all potential sites should be evaluated with the possibility of transitioning to a fixed prosthesis in the future. For example, if implants are planned in the A, C, and E regions and the C region fails, a new implant placement can be planned in the B region. During the initial planning, if the anterior bone volume allows, implants with a diameter of 4 mm or larger are recommended in the anterior region, with modifications to the arch form for posterior support.(Prasad et al., 2013)

14.Mandibular Overdenture Treatment Options

According to Carl E. Misch’s treatment protocol, five different treatment options are available for mandibular overdenture therapy. Each option is determined based on factors such as bone volume, prosthesis stability, and cost.(Table 2)(Lambade et al., 2014)

Table 2. Mandibular Overdenture Treatment Options

Option	Description	Implant Positions	Prosthesis Movements (PM)	Indication
OD-1	RP-5 with Independent Implants in B and D Positions	B - D	PM-6	Cost
OD-2	Implants in B and D Positions Connected by a Rigid Bar	B - D	PM-3 – PM-6	More Stability, Cost Still Matters
OD-3A	Implants in A, C, and E Positions	A - C - E	PM-2 – PM-6	Ideal Posterior Bone Form, Moderate Stability
OD-3B	Implants in B, C, and D Positions (if posterior bone form is poor)	B - C - D	PM-3 – PM-6	Weak Posterior Bone, Moderate Stability
OD-4	Implants in A, B, D, and E Positions with a Rigid Bar and a 10 mm Distal Cantilever	A - B - D - E	PM-2 – PM-6	More Support

Table 2. Mandibular Overdenture Treatment Options

Option	Description	Implant Positions	Prosthesis Movements (PM)	Indication
OD-5	Implants in A, B, C, D, and E Positions with a Rigid Bar and a 15 mm Distal Cantilever	A - B - C - D - E	PM-0	Maximum Stability, Support, and Comfort

If Cost is a Concern:

- OD-1 or OD-2 should be considered.
- OD-3A is suitable if the posterior bone is sufficient and moderate stability is desired.
- OD-3B is preferable if the posterior bone is weak but high stability is needed.
- OD-4 provides greater support and stability.

OD-5 ensures maximum support, stability, and comfort and should be evaluated for prosthetic indication.(Lambade et al., 2014)

15.Overdenture Attachment Systems

O-Ring or Ball Attachments

The O-ring attachment is one of the most widely used stud attachments in dentistry, enhancing retention in implant-supported complete and partial overdentures as well as conventional overdentures. The O-ring abutment has a ball-shaped head that connects to a post or cuff (patrix), with a groove or undercut area (matrix) to hold the O-ring. Typically made from titanium alloy, the O-ring abutment is either screwed directly into the implant or cast into a precious or semi-precious alloy superstructure bar.(ELsyad et al., 2018)

Advantages of o-ring attachments

1. Flexibility and Durability: Allows slight movement of the prosthesis while maintaining strong retention.
2. Self-Aligning Feature: The material's elasticity compensates for minor misalignments, improving fit.
3. Easy Maintenance and Replacement: The retentive component inside the prosthesis can be replaced without altering the implant or bar. (Ohkubo et al., 2004)

Single attachment systems in implant-supported overdenture prostheses

o-ring size

The diameter of the O-ring depends on the available space within the overdenture acrylic:

- Larger O-rings provide greater retention, ease of use, and reduced complications.
- Available in three standard sizes.
- The inner diameter is slightly smaller than the retentive post to ensure a secure grip.
- Hardness is measured on the Shore A scale:
 - o Softest O-rings: 30-40 Shore A
 - o Hardest O-rings: 80-90 Shore A
- Color does not indicate hardness. While black is common, some manufacturers use different colors for standardization or aesthetics.

Materials used: Silicone, nitrile, fluorocarbon (Viton), and ethylene-propylene (EPDM). (Qin et al., 2019)

Locator attachment system

The Locator attachment system consists of a patrix, which is screwed into implants at different heights, and a matrix, which is a replaceable nylon component housed within a metal cap inside the prosthesis. These nylon matrices come in different colors, each representing a specific retention value. This system is particularly suitable for cases with limited interocclusal space and implant angulations of up to 40°.

The Locator system includes abutments compatible with all implant diameters, a metal housing containing a black processing cap (Locator Processing Cap), and interchangeable nylon inserts (Locator Inserts) available in blue, pink, clear, red, orange, and green, each offering different levels of retention. (Miler et al., 2017)

The OD-secure attachment

Compensates for implant angulations up to 30°, while the Xtend housing allows for corrections up to 50°. Its patrix surfaces are coated with titanium nitride for enhanced wear resistance. Designed with a low-profile structure, it has a height of 2 mm. (Midentistry, 2021)

The Locator R-TX system

The Locator R-TX system tolerates implant angulations up to 60° and features a DuraTec coating for increased hardness and wear resistance. Its narrower cavity reduces plaque buildup, and its dual retention surfaces enhance stability. The pink housing includes horizontal grooves for improved prosthetic fixation. (Chavez, 2021)

The optiloc system

Features an ADLC (Amorphous Diamond-Like Carbon) coating, enhancing wear resistance. Its retentive insert is made of PEEK material and accommodates implant angulations up to 40°. Unlike other matrix systems, it allows minimal prosthetic movement without dislodging and always returns to its original position. (Arul & Jebaselvi, 2024)

The locator F-TX system

Is designed for fixed full-arch restorations. Unlike traditional fixed restorations, it does not require cement or screws, relying on a passive fit connection. It provides a removable option for clinicians while remaining fixed for the patient, ensuring aesthetics, cost efficiency, and enhanced comfort. (Amato & Polara, 2018)

The CM-Loc system

Features an abutment without a central retention hole, improving cleanliness. Its retentive insert, made of wear-resistant Pekkton polymer, allows for implant angulations up to 60°. (Naguib et al., 2019)

The locator root attachment system

Utilizes natural tooth roots to retain overdentures or partial prostheses, offering an aesthetic and stable solution for patients who cannot afford implants. It serves as an interim step before implant treatment, helping to preserve bone, maintain facial profile, and support future implant success. Available in straight, 10°, and 20° options, it is suitable for divergent roots. (Miler et al., 2017)

The novaloc system

Ensures retention through a snap-fit mechanical locking mechanism. Its titanium abutment is reinforced with a diamond-like carbon coating, while the matrix is made of PEEK. Designed to tolerate implant angulations up to 40°, it offers enhanced wear resistance. The retentive ring, made of flexible PEEK, comes in different colors based on retention levels and allows slight flexing during insertion and removal. (Szeluga et al., 2008)

The saturno narrow-diameter implant system

Features a straight or 20°-angled O-ball attachment with a micro O-ring for retention. It accommodates implant angulations up to 30.

Hader Bar and Clip System

Introduced by Helmut Hader in the late 1960s, the system was 8.3 mm in height. Today, Hader bar systems are designed with a height of only 3 mm, offering three different retention types for greater flexibility. Compared to O-ring systems, Hader bars allow for a lower-profile prosthetic design. Hader bar overdentures can be designed with a height of 4 mm, whereas O-ring overdentures require at least 5-7 mm, making the Hader bar system more stable and retentive. The cantilever length should be carefully adjusted and should not exceed 10-12 mm. (Singh et al., 2013)

Implant-Supported Overdenture Prostheses and Treatment Approach

If only two implants are used for edentulous mandibular restoration, both should not be positioned anterior to the mental foramen.

Five treatment options are available for mandibular implant-supported overdentures, standardized for patients with Division A anterior bone but modified for Division C-h bone as follows:

- o An additional implant is added to each treatment option.
- o OD-1 is completely removed.
- o OD-2: Applied with three implants (B, C, D).
- o OD-3: Applied with four implants (A, B, D, E).
- o OD-4: Applied with five implants (A, B, C, D, E).

OD-5: Applied with six implants. (Kuoppala et al., 2012)

16. Regional Limitations for Partial Edentulism in the Anterior Maxilla

Implant placement in the maxilla is more complex due to bone resorption, low bone density, and biomechanical challenges. Treatment planning should consider bone grafting, appropriate implant diameter, and positioning. Narrow ridges require narrow implants, which increase stress concentration. Facial cantilevers may cause excessive moment loads, and off-axis occlusal forces can lead to overloading. Low bone density reduces implant support, while palatal bone resorption patterns make implant placement more difficult. (Krennmair et al., 2011)

17. Treatment Options for Partially Edentulous Patients in the Anterior Maxilla

1. Traditional Tooth-Supported Bridge: A practical, low-risk, and cost-effective option but unsuitable for long edentulous spans. It requires tooth preparation and is not ideal for weak abutment teeth.
2. Traditional Removable Partial Denture: While cost-effective, it is the least preferred due to aesthetic concerns and patient discomfort. It may cause rapid deterioration of abutment teeth and basal bone.
3. Resin-Bonded Bridge (Maryland Bridge): A conservative approach with minimal tooth reduction, but unsuitable for large edentulous areas.
4. Implant-Supported Fixed Prosthesis: The most preferred option as it preserves alveolar bone stimulation, requires no preparation of adjacent teeth, and offers long-term success. (Arita et al., 2020)

18. Maxillary Overdenture Options

Maxillary complete dentures are generally better tolerated than mandibular ones. Patients often focus on mandibular restorations first, but after receiving a mandibular implant-supported prosthesis, they frequently seek maxillary implant treatment. However, implant failure rates in maxillary overdentures are higher than in mandibular overdentures. While mandibular implant overdentures offer five treatment options, maxillary overdentures provide only two due to:

- Biomechanical disadvantages of the maxillary bone

Lower bone density and unfavorable force distribution affecting implant stability. (Osman et al., 2012)

19. Maxillary Overdenture Treatment Options

RP-5

- Includes partial posterior soft tissue support
- Supported by both soft tissue and implants
- Requires fewer implants
- Minimum 4 implants required, at least 3 in the premaxillary region
- Key implant sites: Bilateral canine regions, ideally one central incisor, or alternatively bilateral lateral incisors and first premolar areas

- Antero-posterior (AP) spread should be maximized

RP-4

- Fully implant-supported, retained, and stabilized prosthesis
- No soft tissue support
- Requires more implants (typically 6 or more)

Provides greater biomechanical stability (Osman et al., 2012)

20. Biomechanics of Maxillary Overdentures

- Cantilever bars are not recommended due to poor bone quality and excessive load risks.
- Implants should not be placed independently; they must be splinted with a rigid bar.
- AP spread should be maximized.
- Minimum bone height: 15 mm in the anterior, 12 mm in the posterior.
- Bar should be slightly lingual to the original crest and not extend posteriorly.

The prosthesis must allow movement in at least two directions. (Gibrel et al., 2019)

21. Maxillary Overdenture Attachment Options

Hader Clip (for RP-5 Prosthetic Restorations)

- Provides a more rigid structure, functioning similarly to a fixed restoration supporting all 14 teeth.
- Positioned centrally along the midline of the arch.
- A small gap must be left distal to the implant to allow posterior soft tissue movement.
- The prosthesis should extend to cover the tuberosities and A-line, similar to a complete denture design.

O-Ring Attachments

- Positioned more distally than Hader clips, usually just distal to the canine region.
- This allows slight rotation around a fulcrum in the canine or premolar area.

RP-5 Prosthesis Design

- Uses 7 to 10 implants, making it a fully implant-supported and rigid system.
- Functions similarly to a fixed prosthesis but may require a labial flange or bone grafting in the premaxilla due to bone resorption.
- Preserves more bone volume and provides greater stability and security.
- Key implant positions:
 - o Bilateral canine regions
 - o Distal half of the first molar region
 - o Bilateral second premolar regions

At least one anterior implant, typically in the central incisor region (Sutariya et al., 2021)

22. Prosthesis Design and Occlusion

- Implants must be splinted with a rigid bar.
- At least four attachments should be used along the arch.
- The palatal region is usually covered with acrylic.
 - o Removing palatal coverage may cause food entrapment and speech issues.

However, special cases (e.g., strong gag reflex, frequent speakers, new denture users) should be evaluated individually. (Sutariya et al., 2021)

23. Clinical Application and Advantages

- If the central incisor region lacks sufficient bone, alternative implant sites can be used.
- Implant diameter should be at least 5 mm to ensure stability.
- In patients with severe premaxillary bone loss, overdentures provide a reliable support structure. (Mirchandani et al., 2021)

24. Occlusion of implant-supported prostheses

In the selection of occlusion in implant-supported prostheses, the following factors should be considered:

- Number of implants

- Load
- Occlusion of the opposing jaw
- Restorative material used in the opposing jaw
- Parafunctional habits
- Existing type of occlusion
- Occlusal plane
- Interavicular distance
- Dental anamnesis

There are three fundamental principles of occlusion in implant-supported prostheses: increasing the support areas of the prosthesis, regulating the direction of forces, and reducing the amount of force applied to the prosthesis.(Rocha et al., 2023)

25.Occlusion in implant-supported removable prostheses

If the opposing jaw is edentulous, a mandibular overdenture supported by two implants would be a more suitable treatment plan when a flexible attachment that allows movement is used. In patients planned for a mucosa-supported conventional prosthesis in the maxilla, a mucosa-implant-supported prosthesis and bilateral balanced occlusion are recommended for the mandible.For overdentures in patients with a normal ridge, bilateral balanced lingualized occlusion is advised.In cases of severely resorbed ridges, monoplane occlusion should be used. Occlusal planning should be designed according to the type of edentulism, as shown in the table 3.(Table 3)(LORD & TEEL, 1969)

Table 3. Occlusal planning should be designed according to the type of edentulism

Edentulism	Type of prosthesis	Type of occlusion
Complete edentulism	Fixed prosthesis	Canine-guided occlusion
Complete edentulism	overdenture	Bilateral balanced occlusion
Kennedy III and IV	Implant-supported fixed prosthesis	Unilateral balanced occlusion
Kennedy I and II	Implant-supported fixed prosthesis	Canine-guided occlusion

Determining the ideal occlusion type for implant-supported prostheses with a single rule would be misleading.Therefore, each case should be evaluated individually, considering: Dentition of the opposing jaw, prosthetic material, number of implants used and localization of the implants. Based

on these factors, the appropriate occlusion type should be determined. Implant-protective occlusion is an approach aimed at ensuring the long-term success of implant-supported protheses by distributing occlusal forces in a balanced manner. Unlike natural teeth, implants do not have periodontal ligaments; therefore, traditional occlusion principles cannot be directly applied to implants.(Abichandani et al., 2013)

26.Immediate Load Applications in implant dentistry

Immediate loading is a treatment approach that involves placing a temporary or permanent prosthesis immediately after the surgical placement of the implant. Traditionally, the two-stage surgical protocol developed by Brånemark requires a waiting period of 3 to 6 months for the implant to achieve osseointegration with the bone. In contrast, the immediate loading protocol aims to put the implant into function immediately or within a very short period. Immediate Loading and Implant Maintenance.(Misch & Scortecchi, 2005)

27.Immediate Loading Requirements

For immediate loading to be performed, primary stability must be achieved at a torque force of 35 Ncm.

Advantages of Immediate Loading

- Faster treatment process
- No need for a second surgical procedure
- Better preservation of soft tissue form
- Psychological benefits by preventing an edentulous period for the patient

Disadvantages and Risks of Immediate Loading

- Higher risk of complications if primary stability is insufficient
- Micro-movements must be controlled within acceptable limits

Higher failure rates compared to traditional protocols(Tettamanti et al., 2017)

Immediate Loading in Partially Edentulous Patients

The immediate loading concept can also be applied to partially edentulous patients and single-tooth implants. However, due to frequent occlusal contact with opposing teeth, temporary restorations should be carefully designed.

Most clinical studies indicate similar implant survival rates between immediate loading and the submerged two-stage healing protocol. However, this does not mean immediate loading is suitable for all patients. Following biomechanical principles during immediate loading procedures significantly improves implant success.(Huynh-Ba et al., 2018)

28.Dental Implant Maintenance

Regular care and hygiene are essential for the long-term success of dental implants. Patients must attend routine dental check-ups based on their oral hygiene, number of implants, and overall health status:

- First 6 months: Every 1 to 3 months
- Between 1–2 years: Every 6 months

After 2 years: Annually(Humphrey, 2006)

During dental examinations:

- Bone and gum health around the implant should be evaluated
- Radiographic control should be performed
- Occlusion assessment should be conducted

At home, patients should be educated on proper flossing and brushing techniques. Overdenture prostheses should be removed and cleaned every night, using special prosthesis cleaning solutions.(Chen & Darby, 2003)

29.Criteria for Evaluating Bone Loss Around Implants

For an implant to be considered in ideal health:

- Bone loss should be less than 1.5 mm in the first year
- Less than 1.0 mm of bone loss should occur after prosthetic loading
- No exudate (pus) or radiolucent areas (bone loss regions) should be present
- No vertical mobility should be observed
- Periodontal pocket depth should be less than 2.5 mm

Lamina dura (bone border) should remain intact(Galindo-Moreno et al., 2015)

30.Types and Stages of Implant Failure

1. Surgical Failure: Caused by incorrect implant positioning or damage to bone integrity.
2. Failure During Healing: Results from infection, poor bone quality, or implant mobility, leading to loss of stability.
3. Early Loading Failure (within the first year): Occurs due to incorrect prosthetic positioning, excessive occlusal load, or infection, preventing proper osseointegration.
4. Medium-term (up to 5 years) and Late-stage (5–10 years) Failures: Develop due to long-term excessive loading, poor hygiene, or progressive bone loss, leading to implant instability.(Mohajerani et al., 2017)

To prevent implant failure, surgical planning, appropriate loading protocols, and regular maintenance are crucial. Identifying the failure stage and cause enables the implementation of an effective treatment plan, reducing peri-implant diseases and increasing implant success.(Rosenberg et al., 2004)

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The Encoded Discipline in Bone:

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