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Review Article

BIOCOMPOSITION OF DENTAL IMPLANTS

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Abstract: Dental implants are mechanical devices that are designed to substitute individual missing teeth and are the best existing remedy for tooth loss. Modern dental implant design involves devices composed of three different parts—the crown, the abutment, and the implant fixture. The materials and surface treatments used to design the different parts of a dental implant are carefully selected for their functions. The biomaterials selected to construct the crown must be biologically inert to withstand degradation due to acidic foods and aesthetically resemblant of the natural tooth. Alternately, the biomaterials used for the implant fixture target strength, durability, and assimilation into surrounding biological tissues. The implant fixture, or the "artificial tooth root," is the most critical component in terms of biocompatibility because it directly interacts with the jawbone. The implant fixture achieves direct bone to implant contact through osseointegration, which is a key process permitting the biological compatibility of the implant within the body. This paper aims to discuss currently existing dental implants and their relevant features in relation to their use as a biocompatible tooth replacement.

Keywords: Dental implants

INTRODUCTION

Tooth loss is a relevant issue, predominantly in the elderly population, and is triggered by poor oral hygiene, exacerbation of existing cavities, gum disease, and smoking. There are several reasons patients consider dental implantation. Because they visually substitute missing teeth, implants provide aesthetic benefits to the patient. Dental implants also stimulate the production of dense jawbone material, which prevents the sunken-in appearance of the oral

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Dedication: Nana, thank you for always encouraging me to think, ask questions, and challenge the current knowledge. You are my inspiration for pursuing science, and I hope you are as proud of me as I am of you. I am eternally grateful for all you have done for me.

cavity due to teeth loss. Implants also prevent the readjustment of surrounding teeth, which can later lead to other orthodontic complications, including malocclusion. Additionally, dental implants promote the conservation of jawbone. If a fixed bridge is placed in lieu of a dental implant, the jawbone can begin to deteriorate in the region beneath the absent tooth. The longer a patient waits to receive a dental implant, the more likely it is that their jaw deteriorates and would require bone grafting prior to implant placement. Placing implants can also allow for the placement of implant supported dentures, which are implants that support an entire arch of prosthetic teeth with as few as four implants, in a technique known as "all-on-four" [1].

Modern dental implants consist of three parts—the implant fixture, the abutment, and the dental prosthesis. The implant fixture, or "artificial tooth root," is typically made of titanium andis a support that mimics the tooth root. The abutment is a gold, porcelain, or titanium component that is screwed into the implant fixture and provides adequate support for the dental prosthesis. The dental prosthesis, or the crown, is the portion of the implant that visually resembles the tooth [2]. It is screwed into or cemented onto the abutment and is usually composed of porcelain fused to a metal alloy. In some cases, the dental implant can also be completely made of metal or completely made of porcelain. Implants are primarily shaped with the fixture at the base and the crown at the proximal end. The resemblance of these three parts of the implant to the natural tooth is evident (Fig. 1) [3].

Within a dental implant, there are distinct regions of two types. The first type functions to dictate properties that positively impact the implant's biological integration with the surrounding tissue. These properties include osseointegration, inflammation suppression, prevention of infection, and promotion of the growth of surrounding cells and tissues. The second type of region within the implant works to increase the primary stability and durability of the implant [2].

Osseointegration: Osseointegration is defined as direct bone to implant contact without an intermediary connective tissue layer and is a critical component of dental implant assimilation into the jaw. The speed and efficacy of osseointegration is a defining factor dictating the clinical success of a dental implant. The rate of osseointegration of titanium dental implants is directly correlated to the surface roughness, geometry, and chemical composition of the implant. Following initial osseointegration, biomechanical factors of the prosthetic device and patient hygiene are the main factors dictating the implant's long-term success [4].

During osseointegration, activated osteoclasts attach to the fractured regions of surrounding bone, resorbing it to create space for bone reformation. Osteoclasts employ proteolytic enzymes, such as proteases, and hydrochloric acid to dissolve bordering residual bone. Growth factors such as BMP (bone morphogenic protein), TGF-β (transforming growth factor-beta), and PDGF (platelet derived growth factor) are then released from the bone matrix to initiate the formation of new bone. This occurs through the activation of osteoblasts, which create new bone by forming an organic matrix and incorporating calcium phosphate for mineralization. Additionally, proteins adsorbed to the implant surface, such as fibronectin, increase the attachment of bone progenitor cells. There is consistently a thin protein layer present between the implant and the bone, and the mechanical stability of the implant within the newly formed bone is ensured through interlocking with the implant surface [5].

Chemical composition: The chemical composition of the implant is one major factor affecting speed of osseointegration. Most implants are composed of commercially pure titanium or titanium alloys. Pure titanium has multiple degrees of purity, characterized by different concentrations of carbon, oxygen, and iron. Titanium alloys are typically composed of Ti_6Al_4V, a grade 5 titanium alloy, which has a higher yield strength than pure titanium. The chemical composition of the surface of titanium implants affects their interaction with surrounding materials since hydrophilic surfaces tend to interact more successfully with biological fluids [6].

Surface treatments: An increased surface roughness is associated with greater osseointegr-ation. Surface roughness is characterized at three levels of intensity—macroscale topography, microscale topography, and nanoscale topography. Macroscale topography describes fluctuations on the implant surface greater than 10 ġm and is associated with implant geometry. The use of a higher roughness profile on the macroscale level is associated with greater success of early implant fixation as well as increased long term mechanical stability of the implant. Microscale topography describes surface changes ranging from 1–10 ġm. An increased surface roughness at the microscale level maximizes the interlocking between mineralized bone and the surface of the implant. Surface fluctuations of less than 1 ġm are characterized by the nanoscale level. An increased surface roughness at the nanoscale level corresponds with greater osseointegration due to an increase in the adsorption of proteins and adhesion of osteoblastic cells [6].

Several surface treatments have been used to increase dental implant osseointegration rates. These include titanium-plasma spraying, grit-blasting, acid-etching, osteoconductive calcium phosphate coatings, and anodization.Titanium-plasma spraying involves the injection of titanium powders into a plasma torch at a high temperature. The powders are then projected onto the implant surface, where they condense to form a uniform film 40-50 ġm in thickness. Titanium-plasma spraying coated surfaces typically have a surface roughness of about 7 ġm, which increases implant surface area and tensile strength at the bone-implant interface. Grit-blasting consists of the implant being blasted with hard ceramic particles, with different surface roughnesses being produced using different sized ceramic particles. Acid-etching uses strong acids including HCl, HNO_3, H_2SO_4, and HF to produce micropits on titanium surfaces that enhance osseointegration. Osteoconductive calcium phosphate coatings are mainly composed of hydroxyapatite. The release of calcium phosphate increases body fluid saturation in surrounding regions and precipitates a biological apatite, which serves as a matrix for osteogenic cell attachment onto the implant surface. Anodization of the titanium surface of implants thickens the external oxide layer, which is then dissolved along current convection lines in a strong acid, forming microor nano-pores that increase osseointegration [6].

Current dental implants

Crown: Modern dental implants are well-documented and widely used. The current designs are a good replacement for a missing tooth both aesthetically and functionally but can also be improved. In current dental implants, the porcelain-fused-metal (PFM) crown is a good replacement for the crown of a tooth and is currently standard-of-care. The implant crown can be custom-made to look aesthetically similar to a natural tooth (i.e., matching the shade of their other teeth), giving patients confidence in their appearance after replacement. The crown also functions similarly to a natural tooth allowing for seamless use alongside the remaining natural teeth. Including a metal in the ceramic structure allows the crown to possess the aesthetic properties of a tooth and increase its mechanical properties. Drawbacks of the PFM implant are derived from the metal portion of the implant. The metal may cause allergies, gum staining, and the release of metal ions into the body. Additionally, the aesthetic of metal is inferior to an all-ceramic crown. Currently, there is a push to start using these all-ceramic systems as an alternative crown, but the poor fracture resistance reduces the lifespan of these crowns and thus makes them contraindicated in many patients, especially younger patients who are receiving crowns or implant crowns. Ceramic crowns, however, possess an almost exact aesthetic similarity to natural teeth. With the improved techniques for making modern ceramics, their uses in dentistry have widely increased [7].

The biomaterials used for the crown have a significant impact its longevity. The ceramic portion of the metal ceramic system is important for making the implant biocompatible and bioinert and imparts compressive strength on the material. Ceramics are highly biocompatible, so they can be implanted with little risk of an adverse reaction when they encounter biofluids in the mouth. Additionally, the inert properties of ceramics allow for minimal degradation of the crown with time. This is especially important in the mouth where teeth are exposed to acidic foods/drinks or salivary enzymes, both of which can contribute to chemical and mechanical degradation of the implant, which would decrease the implant's lifespan and may require replacement of the crown/implant. Ceramics also have high compressive strength which is important for withstanding high compressive forces during chewing. The metal portion of the metal ceramic is important in imparting mechanical properties on the crown, such as increased fracture resistance. This limits the number of crack failures of the crown [8].

Abutment and implant fixture (Straumann® Bone Level Implant): The Straumann® Bone Level Implant is positioned on the same level as the bone and focuses on providing bone level solutions.

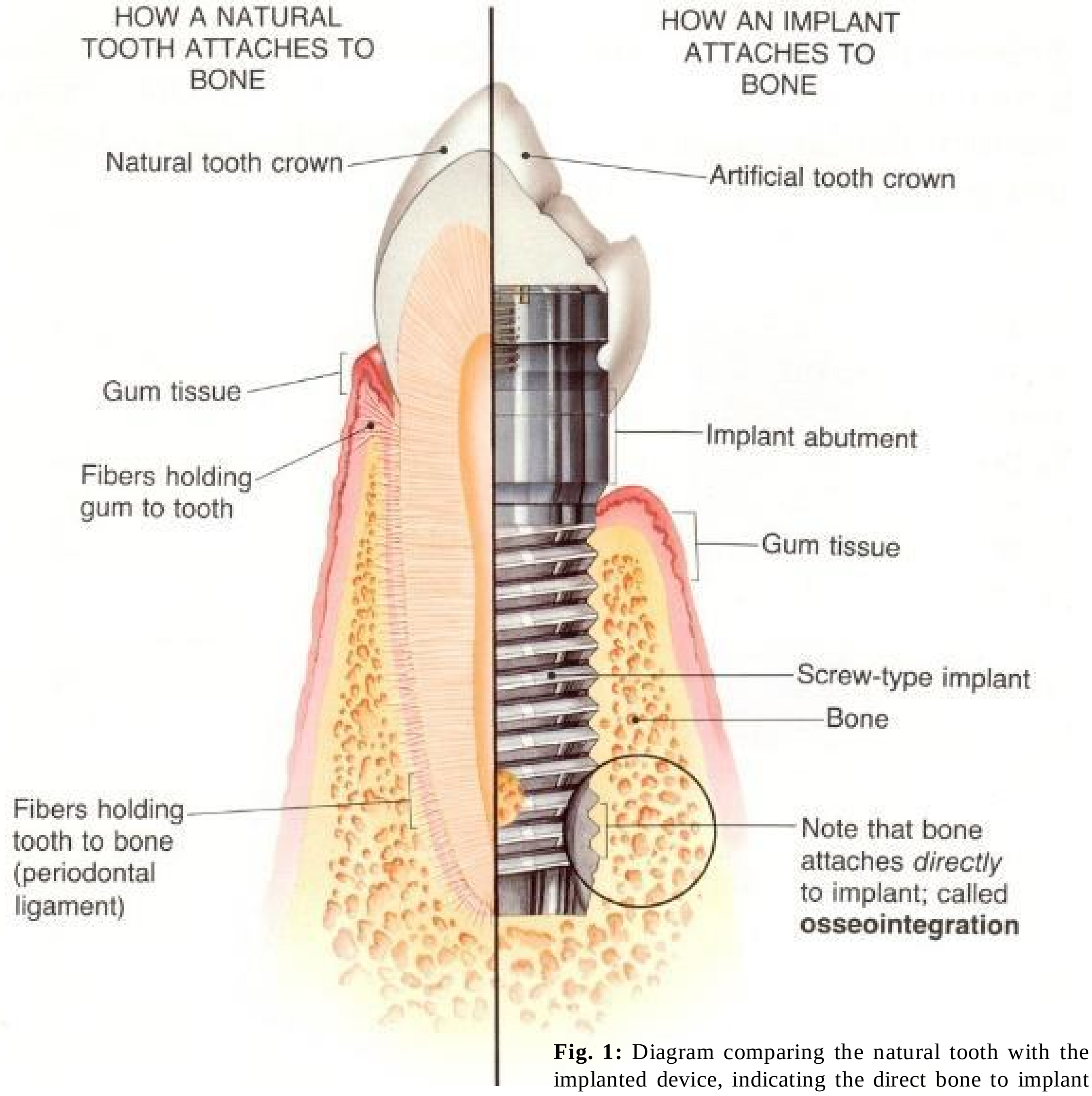

Fig. 1: Diagram comparing the natural tooth with the implanted device, indicating the direct bone to implant contact achieved by osseointegration in the implant fixture.

Fig. 2: Diagram of the Straumann® Bone Level Implant depicting the SLActive® surface treatment and the titanium implant material.

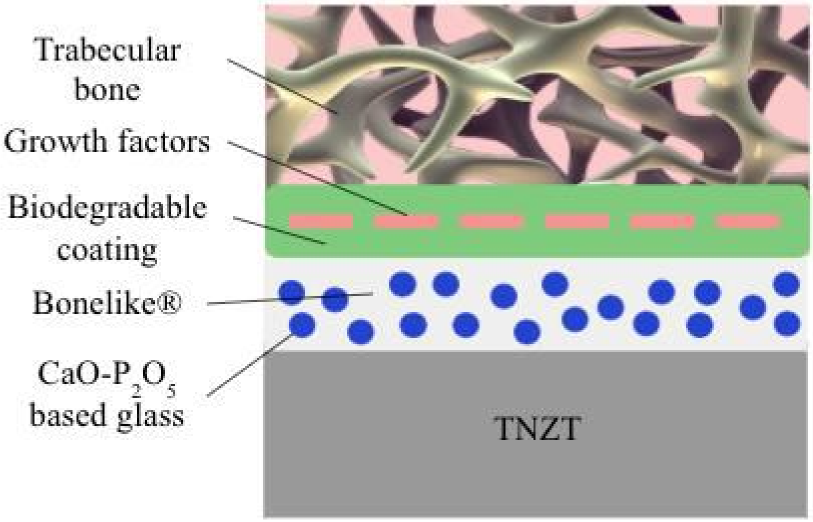

Fig. 3: Diagram of Potential New Implant Design

This commercial implant is made entirely of titanium with a specific surface treatment called SLActive® [9]. (Fig. 2). The titanium implant material has excellent biocompatibility due to the formation of a stable oxide layer on the surface [10]. In commercially pure titanium, minute quantities of contaminants are added, such as iron for corrosion resistance and aluminum for strength [10]. This gives the implant decent mechanical properties and the ability to resist corrosion.

One of the main characteristics of this Straumann® implant is the use of the revolutionized SLActive® surface treatment. SLActive® is a hydrophilic, chemically active surface [11]. It is engineered through using coarse grit-blasting and acid-etching to create the rough surface topography. The surface is then rinsed under nitrogen protection to prevent exposure to air and contaminants. Subsequently, the nitrogen-treated surface is stored in a sealed container along with isotonic NaCl solution [12]. This specific treatment process ensures a hydroxylated and hydrated surface. This design is also able to maintain a high surface energy by reducing the number of contaminants, such as hydrocarbons and carbonates, that adsorb onto the surface. Higher surface energy was proven to increase bone responses and aid osseointegration [12].

This surface treatment has a variety of effects on post-implant recovery. A hydrophilic surface, rather than a hydrophobic surface, provides a larger surface area for protein adsorption and fibrin network formation.[13] These conditions are ideal for blood clot formation and the initiation of the healing process. TheSLActive® surface also promotes bone vascularization through greater stimulation of blood vessels compared to hydrophobic surfaces.In addition, the surface hydrophobicity boosts bone regeneration and bone-to-implant contact (BIC), facilitating further osseointegration. Overall, because of these improvements in the healing process, the surface reduces healing time from 6-8 weeks (with a hydrophobic surface) to 3-4 weeks [13].

Other features of the Straumann® implant include a Bone Control Design that specializes in preserving crestal bone. This design of the abutment and fixture include 5 main features: microgap control, optimal positioning of smooth and rough surface, implant surface osseoconductivity, a biomechanical design that optimizes fatigue strength, and a horizontal offset of the biological distance to help keep the microgap away from bone [9]. Another main feature of the implant is the CrossFit® Connection between the abutment and the fixture. This prosthetic connection provides increased flexibility and stability through its conical connection, gives a more precise and clear insertion through 4 grooves, and prevents rotation of the implant [9].

The advantages of the Straumann® implant include increased osseointegration capabilities because of the application of the hydrophilic and chemically active surface. Its unique features, such as the Bone Control Design and the Cross Fit Connection® explained above, are also beneficial compared to other commercial implants; however, its pure titanium implant material could lead to a higher risk of corrosion, which is unfavorable and could be improved upon.

Commercial Variants: Commercial variants of the Straumann® Bone Level Implant include the similar model called the Straumann® Soft Tissue Level Implant. This implant is positioned on the tissue level, instead of the bone level, meaning that the abutment will rise slightly above the bone after implantation. This mimics the emergence of the natural tooth and eliminates any need for healing abutments or soft tissue procedures post-implantation [14]. Another variant that is now more widely used is the Straumann® PURE Ceramic Implant. Ceramic implants are popularly used for aesthetic purposes. The ivory color of ceramics allows for a more natural appearance, which is more aesthetically appealing to patients [15]. In addition, pure ceramic implants are more effective in treating patients with a thin gingiva biotype. Patients with thin gingival biotype have less tissue covering the gums, which causes the underlying root to appear translucent [16]. Therefore, the use of a ceramic implant is primarily for aesthetics. However, patients with thin gingiva are also more prone to gum diseases and infection, and because corrosion of the metal portion of implants may cause increased susceptibility to bacterial accumulation, it is less favorable to use metal implants in this specific subset of patients.

Costs: Dental implant costs place a large financial burden on patients, even those that are insured. A single dental implant has an average cost of $3,000 to $4,500 [17]. The cost continues to increase significantly for the first few teeth that need to be implanted. The cost reaches a maximum average cost of around $34,000 for top and bottom supported dentures (all-on-fours). The financial burden is placed mostly on the patient, as most insurance companies consider implants to be purely aesthetic procedures, rather than procedures that are necessary for maintenance of good oral and systemic health. As such, most insurance companies only cover between 15 and 50 percent of dental implant costs [18].

Advancements in Technology: Recently, a newly manufactured titanium alloy, Ti-20Nb-10Zr-5Ta (TNZT) has been developed, along with a dual coating in which the bottom layer is a glass-reinforced hydroxyapatite coating patented under the name Bonelike® and the top layer is a biodegradable coating that releases growth factors involved in bone healing. (Fig. 3).

TNZT is a new quaternary titanium-based alloy with 20% Niobium, 10% Zirconium, and 5% Tantalum. No adverse effects on apoptosis, growth delay, cell survival, or alkaline phosphatase activity have been observed during testing, suggesting that the alloy has good biocompatibility for dental implants [19]. In addition, TNZT has been reported to have good osseoconductivity which allows for better osseointegration [20]. Many of the characteristics of TNZT are better than that of titanium alone. For example, TNZT has greater ultimate tensile strength and hardness than titanium, indicating that it is better able to withstand applied stresses [21]. TNZT also forms a two-layer passivation film which confers greater corrosion resistance and bioactivity to the alloy than titanium alone [22].

Double layer coatings of implants (i.e., Bonelike®) greatly aid the osseointegration process by improving the fixture stability so implant failure will be less likely to occur, and providing quicker recovery time so that the abutment and crown can be installed sooner. The biodegradable top layer in initial contact with the trabecular bone after implantation of the fixture can be the biodegradable composite of calcium alginate and gelatin. The alginate particle size and viscosity can be modified to achieve optimal degradation rate while the gelatin particles bind to the growth factors involved in bone formation [22,23]. As the coating degrades, the growth factors can be slowly released. These growth factors include bone morphogenetic protein (BMP), platelet derived growth factor (PDGF), and transforming growth factor beta (TGF-ā), which are secreted by osteoclasts to signal bone formation [25]. Release of these growth factors from the material surface signals for a quicker arrival of osteoblasts to form new bone. The coating also encourages the formation of hydroxyapatite on the surface, which is an important mineral in bone and enamel [24].

To add Bonelike® to new implant models, a simple dip-coating method can be used [24]. In this process, the implant fixture is immersed in a solution of the coating and then slowly removed. Once the solvent evaporates, the biodegradable coating remains on the surface [26]. Although the processing method for this coating has never been tested on TNZT, it has proven to work on Ti-6Al-4V [24]. Thus, it is possible that the coating will be successful on TNZT as they are both titanium-based alloys.

Degradation of the top layer would result in the exposure of the Bonelike® glass-reinforced hydroxyapatite coating. This coating contains CaO-P_2O_5-based glass that promotes bone bonding to the implant fixture by providing an acceptable surface the incorporation of ions such as Na^+, Mg^{2+}, and F^-. [27]. The osteoblasts that have been called to the material surface by the biodegradable coating can then easily form collagen and bone mineral deposits on the implant surface with these ions [28]. Tests on implants with a Bonelike® coating have shown improved primary stability suggesting that Bonelike® significantly contributes to and hastens the osseointegration process [29].

To add the Bonelike® coating, the ion implantation surface modification process will be used. In this process, the ions that make up the coating will be accelerated to high velocities using high-vacuum technology and bombarded into the TNZT surface. The high kinetic energy associated with these ions will be enough to penetrate the surface upon impact, causing the ions to be incorporated into the atomic network of the material. Thus, Bonelike® becomes an integrated part of the TNZT implant fixture rather than a simple coating. This process removes the risk of delamination associated with plasma-sprayed coatings used on dental implants today [30].

Disadvantages of Newer Technologies: The ion implantation method for adding the hydroxyapatite coating is very expensive and would increase the cost of dental implants by a significant amount [31]. However, this method is the most sustainable over long periods of time and would be advised for younger patients who need the implant to last for many years. For older patients, the standard plasma-spraying method can be used to add the Bonelike® coating as their implants would not have as long of a lifespan. Risk of delamination is alsominimal for shorter periods of time [32].

The optimal degradation rate has not yet been researched or determined. Thus, a lot of time must be dedicated to finding this optimal rate as well as the coating composition necessary to achieve such a rate before the implant can be considered for commercial use. The degradation rate must be relatively fast as the permanent surface must be exposed to the trabecular bone for osseointegration to occur. However, a degradation rate that is too high could lead to toxic levels in the implantation area, disrupting homeostasis and causing complications [24].

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