Dental Implants in Relation to Bone Density

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Titanium has been the material of choice for dental implant fixtures due to its exceptional qualities, such as its excellent balance of rigidity and stiffness. Since zirconia is a soft-tissue-friendly material and caters to esthetic demands, it is an alternative to titanium for use in implants. Nevertheless, bone density plays a vital role in determining the material and design of implants. Compromised bone density leads to both early and late implant failures due to a lack of implant stability.

Keywords: dental implants ; titanium ; zirconia ; biomaterial ; bone density

1. Introduction

Dental implants generally represent the go-to procedure for replacing missing teeth because of their high success rate and attractive results. However, compromised bone quality leads to both early and late implant failures in 7.7% of cases [1]. According to this result, achieving initial stability in low-density bone, which is essential for osseointegration, is a challenging task. With the advancement of technology, numerous studies strive to enhance fixture designs and surgical techniques based on soft bone [2][3][4]. The factors that can affect the success rate of dental implants include implant material, implant design, surgical technique, patient health, or host bed [5].

Dental implant materials and designs (length, diameter, and macro- and microgeometry) affect how much stress and strain develops around the peri-implant tissue, which indicates the chance of successful osseointegration [5][6]. Consequently, the incompatibility between the elastic modulus of the implant material and bone may cause the “stress-shielding” phenomenon, which is related to peri-implant bone resorption [7][8][9]. In other words, the closer the elastic modulus implants are to the bone tissue, the better the distribution of tension. To lessen this difference, numerous studies have suggested developing either porous implants that serve as a scaffold for internal bone growth and lower the modulus of elasticity or innovative materials alloys with lower moduli [10][11][12].

2. Dental Implants in Relation to Bone Density

2.1. Bone Response to Dental Implant Materials

Both biomechanical and biological events can be achieved by osseointegration, referring to a direct bone–implant interface without the interposition of non-bone tissue—a higher degree of osseointegration results in the increased function and primary stability of dental implants [13]. Biomechanical factors are related to the clinical bone response to surgically placed dental implants at the time of insertion. Related factors such as surgical technique, bone density, and the utilization of adjacent graft material and device capabilities are crucial to encouraging and achieving initial bone growth. This initial stability must persist throughout the demineralization phase of bone injury. At 5 or 6 weeks, basic multicellular unit (BMU) remodeling begins, replacing the woven bone with more dense lamellar bone. The bone mineral density around the implant body was then increased for up to two years [14][15].

As well as the implant-related factor and prosthetic relevance (prosthetic design, force magnitude and direction, and load distribution) [16], one of the critical parameters for achieving both osseointegration and mechanical stability is the compatibility between the bone quality of the patient and the stiffness of the implant [9]. As a result, to optimize implant design based on the patient’s specific bone quality, the properties of the dental implant should be correspondingly adjusted.

2.1.1. Bone Density

Bone density, often known as bone quality, refers to the internal structure of bone [17]. Depending on the mechanical properties of the bone, bone quality can be divided into two aspects: density and modulus of elasticity [18]. Regarding bone structure, cortical bone is a crucial feature affecting the primary stability of implant placement, whereas cancellous bone is related to blood supply [19]. According to Misch's classification [20], bone is categorized into the four following types according to the mineralized density and cortical thickness:

D1 bone is primarily dense cortical bone.

D2 bone comprises dense to thick, porous cortical bone with coarse trabecular bone underneath.

D3 bone is composed of thinner porous cortical bone and fine trabecular bone.

D4 bone comprises only fine trabecular bone.

Generally, the bone quality depends upon the jaw location, showing that the mandible surrounding the implant is superior in quality to the maxilla. Significant differences exist between healthy and medically compromised subjects, age, and gender. For instance, Young's modulus of bone can drop by up to 40 to 50% in an osteoporotic patient compared to a normal patient [21]. Regarding gender, males have higher mean bone density values at implant sites than females because of hormonal differences. Furthermore, older females have been found to have lower bone mineral densities than older males [22].

2.1.2. Bone Remodeling and Bone Density

Peri-Implant Bone Strain

Mechanical loads result in bone apposition and deformation or strain, which preserve bone mass and structure through remodeling and modeling processes. Frost's theory proposes that strain magnitude is the stimulus for bone functional adaptation. Regarding loading, the term "strain" describes the relative alteration in bone length or the deformation of bone tissue. Bone resorption occurs when the strains are between 50 and 100 microstrains. In contrast, pathologic bone occurs as microdamage or fracture if the strains have limited bone capacity or greater than 25,000 microstrains. There is a short window, between 1500 and 3000 microstrains, where non-physiologic or mild overloading causes bone gain [23][24].

Stress Distribution in Peri-Implant Bone

The density of each bone varies in strength and impacts elastic modulus, which influences the distribution of stress and strain at the bone–implant contact and the BIC (bone–implant contact) percentage. Low cancellous bone density increases bone strains while decreasing implant stability, which may result in implant failure. In addition, low bone density can also make it more challenging to place the implant in the desired location and angle. The initial bone density provides mechanical immobilization during healing and better stress transmission from the prosthesis to the bone–implant interface [25]. Consistent with previous studies [26][27], higher stress levels were observed in D4-type bone compared with the other bone types. The stress was generally concentrated in the cervical part of the implant socket. In other words, decreased bone density and cortical bone thickness increase the stress on the bone and implants, which can result in bone resorption and implant failure.

In terms of mechanical incompatibility, differences in the elastic modulus of bone tissue and implant materials induce "stress shielding" by absorbing tension and transferring less stress and deformation to the bone tissue, leading to peri-implant bone loss and aseptic implant loosening [28]. In other words, the closer the elastic modulus implants are to the bone tissue, the better the distribution of tension. However, finite element analysis shows that using softer materials with similar strength to the bone provides no benefits in better stress distribution to the peri-implant bone. For example, polyetheretherketone (PEEK) material does not affect the yielding or fracture of implant components; using PEEK as an implant or abutment results in more significant deformation than titanium under static load [29].

Clinical Assessment Tool

Insertion torque (IT) and resonance frequency analysis (RFA) are clinical measurements of implant stability. The insertion torque value (ITV) represents the resistance to a rotational load against the implant to the bone during implant insertion measured in Ncm [30]. According to Aparicio and colleagues, 30 to 50 Ncm provides acceptable implant stability. Some clinicians claim that a high ITV can act as a stimulus for faster osseointegration. A systematic review stated that a high ITV is required for immediate or early loading [31].

ITV, however, is largely dependent on the area of contact with bone, notably the cortical layer [32]. Moreover, the implant-cutting design capacity and bone friction are crucial determinants of distinct bone effects, resulting in high or low ITV [33]. A retrospective study [34] evaluating the mechanical effect of a drilling technique based on bone quality discovered that the bone type and implant diameter significantly influenced ITV. Compared to bone types 3 and 4, type 1 demonstrated a higher ITV. Even if the dense bone type achieves a high ITV value, the marginal bone may lose mean bone mass due to excessive stress and strain.

RFA is a different technique that works by sending a frequency signal to a screwed transducer, which causes the implant to vibrate. The RFA output is expressed as an implant stability quotient (ISQ). The function of the stiffness of the bone-to-implant contact during treatment and follow-up is indicated by the greater ISQ value [35].

Histological Assessment Tool

The higher ISQ value indicates the function of the stiffness of the BIC. The BIC ratio is correlated with the biomechanical properties of the bone-to-implant interface and increases during bone healing [36]. Histological analysis of bone-to-implant interfaces has determined the presence of mineralized tissue in contact with the implant surface rather than fibrous tissue. Nonetheless, it is still being determined how the BIC % can be translated into osseointegration [37]. According to Albrektsson and coworkers [38], good integration accounts for 60% of BIC. Different results can be obtained depending on the bone type, healing time, and implant type.

2.2. Material Used for Dental Implants and Their Properties

Titanium has recently become the material of choice for dental implant fixtures due to its exceptional qualities and excellent balance of rigidity and stiffness. Since zirconia is a soft-tissue-friendly material and caters to aesthetic demands, it is an alternative material to titanium implants. Additionally, PEEK is a polymer material with excellent mechanical properties and superior biocompatibility because it has a low Young's modulus comparable to surrounding bone, which influences an optimal load transfer [39].

2.2.1. Biomaterial of Dental Implants

Metal and Metal Alloy

Titanium and Ti-6Al-4V

Titanium is a frequently used material for dental implants, mainly because of its biocompatibility and capacity to promote osseointegration. The ability of titanium metal to react with air and generate hydroxyl and hydroxide groups endows it with a high capacity for resisting corrosion. This reaction results in the formation of titanium dioxide, which is the most reported in dental implant fields [40]

Grade IV CpTi is the most commonly utilized variety due to its high oxygen content (0.4%) and, thus, excellent mechanical strength. The alloy Ti-6Al-4V, often known as grade V titanium, is widely used in orthopedics because of its superior strength and lower Young's modulus [41]. However, aluminum (Al) and vanadium (V) may affect bone mineralization and type IV allergic reactions, respectively [42]. To avoid an adverse biological response, vanadium-free alloys and non-toxic components such as Nb, Ta, Zr, and Pd are being developed [43].

Titanium and Titanium–Zirconium Alloy

A novel alloy (Roxolid®, Straumann, Basel, Switzerland: TiZr1317) has been produced based on the binary formation of 83–87% titanium and 13–17% zirconium [44]. It outperforms CpTi and Ti-6Al-4V in terms of tensile (953 MPa) and fatigue strength (230 N) [45]. Furthermore, this alloy material exhibits good biocompatibility as pure titanium [46].

Titanium Alloys in 3D Printing

In recent years, 3D printing technologies, also known as additive manufacturing (AM) technologies, have been successfully applied in implant dentistry because they are the alternative method for generating implant products. Moreover, they have allowed for the fabrication of custom implants with microscale resolution. Metallic implants were frequently created using selective laser fusion (SLM) and electron beam fusion (EBM) procedures [47].

Ceramics

For people concerned about a metallic appearance in the esthetic zone or metal allergies, ceramics are an alternative material to titanium [4]. Ceramics are known as inert materials and have good physical properties. They are widely used as a coating material for metal implants [48] and a substrate for fabricating dental implants [49]. Presently, commercially available zirconia implant fixtures involve Y-TZP and ATZ. Details on the manufacturer, brand name, material, and design of the zirconia implant system are given by Ban [50].

Yttria–Tetragonal Zirconia Polycrystal (Y-TZP)

Zirconium dioxide (ZrO_2), often known as zirconia, is a polymorphic material occurring in three temperature-dependent forms: monoclinic (stable from room temperature to 1170 °C), tetragonal (from 1170 to 2370 °C), and cubic (from 2370 °C to the melting point, 2680 °C). When cooling, there is a significant alteration in zirconia unit cell volume, resulting in structural defects that affect the mechanical properties. Because of the spontaneous phase shift of zirconia from tetragonal to monoclinic, doping agents (CaO, MgO, $Y2O_3$) are used to stabilize the structure to create partially stabilized zirconia (PSZ) or tetragonal zirconia polycrystal (TZP) [51][52]. The microstructure of 3Y-TZP ceramics for dental applications comprises 3 mol% yttria as a stabilizer and up to 98% small equiaxed tetragonal grains, occasionally with a small amount of cubic phase. The mechanical characteristics of 3Y-TZP depend on the grain size, determined by the sintering temperature [53][54].

Alumina-Toughened Zirconia (ATZ)

ATZ, a zirconia–alumina composite, is a composite ceramic material of 20 vol% alumina and 80 vol% zirconia with 3 mol% yttria. The addition of alumina significantly improves flexural strength, fracture toughness, and resistance of the material to surface degradation [55]

Polyetheretherketone (PEEK)

PEEK has been used as an alternative to metals for implants since 1998. It has emerged as an option for individuals desiring metal-free restorations in cases of bruxism and allergic responses. Due to its stiff semicrystalline nature, hardness resembling bone, excellent mechanical capabilities, and superior biocompatibility, PEEK is employed as a biomaterial for implant rehabilitation [39].

2.2.2. Functional Properties of Dental Implant Materials to Bone Density

The mechanical properties of implant materials, such as stiffness, strength, ductility, and toughness, describe their capacity to withstand forces and displacements measured by uniaxial tensile tests [56]. Stress, which defines the force applied to a material, is classified into three types: tensile, compressive, and shear.

Strength is generally defined as the ability of the prosthesis to withstand applied stress without fracture (ultimate strength) or permanent deformation (yield strength). As a property, strength is not as reliable for estimating the survival probabilities of brittle material prostheses over time compared to fracture toughness, which more clearly describes the resistance to crack propagation of brittle materials [57]. Flexural strength, also called bending strength or modulus of rupture, is a strength test of the material's ability to sustain bending forces applied perpendicular to its longitudinal axis [58].

Elastic modulus, measured by the ratio of elastic stress to elastic strain, is a term used to describe a material's relative stiffness or rigidity. This property impacts the strength and fatigue strength of the materials as well as the functionality of manufactured implants [28].

Ductility represents the ability of a material to resist a sizeable permanent deformation under a tensile load up to the point of fracture. For example, material A is the most ductile, as shown by the most extended plastic strain range. In contrast, material B is brittle, defined as having no plastic deformation and breaking at the proportional limit [57].

Elastic Modulus, Stiffness

After an implant completes osseointegration, the chewing stress is transferred to the bone tissue surrounding the implant body. As a result of the mismatch between the stiffness of the implant material and the peri-implant bone, the stress imbalance can lead to marginal bone loss and implant failure [59]. This stress-induced marginal bone destruction can be described using the "composite beam analysis" principle. In the case of two materials with different elastic moduli, the primary point of contact between the two materials is where the greatest stress is concentrated [60]. According to Hooke's law, material stiffness depends on its modulus. In the case of the bone–implant system, the bone tends to create more significant deformations. Thus, controlling the variables determining how to reduce the transferred stress is critical, including load type, implant treatment protocol, design component, and peri-implant bone quality [61]. Ti-6Al-4V alloy is the most frequently utilized in the fabrication of dental implants because of its superior elastic modulus and tensile strength [62].

PEEK is widely used to replace titanium or zirconia implant materials because carbon fiber can be added to it to produce carbon fiber PEEK (CFR-PEEK) with varying elastic moduli, which are within the range of the bones' elastic modulus [63] [64]. Interestingly, 30% carbon fibers PEEK (30CFR-PEEK) shows higher stress concentration and deformation at the bone–implant interface, even though reinforcing PEEK with carbon and glass fiber—by determining the optimum quantity, size, and shape of carbon fibers—is the most effective way to improve mechanical properties and prevent stress shielding. However, these drawbacks can be lessened using 60% carbon fibers PEEK (60CFR-PEEK) [65].

The implant geometry significantly affects the implant treatment because it can enhance the mechanical stress transmitted to the bone tissue, causing marginal bone loss [66]. To be more precise, unbalanced load distribution can be improved by modifying implant macro- or microgeometries. According to one literature review, a hybrid design, which combines conical and cylindrical forms, has the highest primary stability because it can distribute stresses more uniformly and incorporate more bone. A conical design, which is wider at the base and narrower at the top, also provides better initial stability and load distribution. This result can reduce marginal bone loss when compared to a cylindrical form [67]. In cases requiring immediate implant insertion, conical implant systems with double threads and a low thread helix angle should be used [68].

The higher the thread depth, the more the surface and the load distribution increase. Greater thread depths may benefit the more excellent functional surface, particularly with softer bone and high occlusal stresses [69], while axial forces distributed as compressive forces with square and buttress threads can be transformed into shear and compressive forces using V-shaped reverse buttress threads [70]. Thread designs with a depth of 0.34 to 0.5 mm and a width of 0.18 to 0.3 mm are reportedly advantageous [70].

The overall success of dental implants also depends on other factors, including the type of implant, prosthetic connection, and the surgical technique.

First, the implant types can be categorized into one-piece and two-piece implants. Microgaps between the implant fixture and the abutment in two-piece dental implants have been associated with microleakage and bacterial contamination [71]. According to the in silico study [72], in comparison to one-piece dental implants, there were higher stress values found in the crestal bone surrounding two-piece implants. These results are used to explain the higher levels of peri-implant marginal bone loss in two-piece dental implants compared to one-piece implants.

Second, many studies have compared external and internal connection types of implants. A retrospective study compared survival rate and peri-implant marginal bone loss between different types of connections. Marginal bone loss was higher in the area around the implants with an external abutment connection after the 1-year follow-up. After five years, there was no apparent distinction between the groups with internal and external connections [73].

Thirdly, the surgical technique plays a critical role in achieving primary stability when placing dental implants in bone that is primarily composed of medullary tissue (D3-D4). There are various surgical techniques suggested to enhance the primary stability in the low-density bone, such as undersized drilling, osteotome technique, piezoelectric bone surgery, and magnetodynamic surgery. Several studies have proved that osseodensification, underpreparation, or expander techniques improved the primary stability of low-density bone, while conventional drilling obtained lower ISQ values [2][3].

Fracture Resistance

ISO 14801:2016 [74] describes a method for evaluating fracture resistance appropriate for in vitro testing. Several studies have been conducted to assess the fracture resistance behaviors (including fracture load and survival probability) of dental implants.

Implant-supported restoration using a titanium abutment and metal–ceramic crown, which has a high success rate of about 95%, is one of the traditional treatment options of choice [75]. Due to its outstanding esthetics, biocompatibility, and mechanical properties, zirconia is a considerably suitable material for constructing implant abutments or crowns in the anterior region [76].

3.2.3. Biological Properties of Dental Implant Materials to Bone Density

Biological reactions at the implant surface and bone contact are critical to the longevity of implant osseointegration and the function of the prostheses. The titanium surface interacts with water molecules and mineral ions during surgery. The surface polarity shifts and the plasma protein (albumin) binds to the surface. After that, the plasma proteins placed by the extracellular matrix protein (vitronectin) aid in cell adhesion. Cells attach to the titanium surface by binding to the vitronectin coating and other extracellular matrix proteins. After one week of implant insertion, the first bone, known as the “woven bone”, contacts the implant surface. The woven bone is then replaced by lamellar bone via the process of bone remodeling. This process may continue for years, depending on the stress distribution surrounding the implant and the bone [77][78].

Titanium is a well-known biomaterial for dental implants since it is inert and does not stimulate foreign body responses. The biomaterial serves as a scaffold for bone growth. The biomaterial's macro- and microporosity allows osteogenic cells and blood vessels to invade, proliferate, and differentiate inside the biomaterial particles. Several surface modification techniques have been developed to improve the surface biocompatibility and bone response surrounding the implant, allowing for faster osseointegration and early loading [79].

Zirconia implants have been investigated in recent years. Zirconia is a chemically inert biomaterial with minimal local or systemic adverse effects, good cell adhesion, great tissue response, and biocompatibility with the nearby bone and soft tissue [80]. Numerous studies have shown that zirconia implants have an osteoconductive characteristic after implantation and do not have any cytotoxic effects on the bone or fibroblast [49].

PEEK is a potential alternative material that has been utilized in dental implantology due to some negative aspects of titanium, including esthetic expectations, hypersensitivity reactions, and stress-shielding phenomena [63]. Even though this material has excellent biocompatibility and no cytotoxicity, it performs poorly osseointegration than titanium due to lower BIC area, less osteoblast differentiation, and less osteoconductive [63][81]. Increases in the hydrophilicity and roughness of PEEK materials can be generated via nanoscale surface treatments to overcome these drawbacks.

An increasing number of surface modifications are being introduced despite the majority of studies comparing machined surfaces with new rough surfaces [82]. Shalabi and coworkers [83] found positive correlations between surface roughness, bone-to-implant contact, and pushout strength. Surface roughness enhances osseointegration, stimulating bone formation and preventing bone resorption. Albrektsson and Wennerberg [84] classified the roughness of implant surfaces into four groups: smooth surfaces (Sa value of <0.5 μm), minimally rough surfaces (Sa value of 0.5–1 μm), moderately rough surfaces (Sa value of 1–2 μm), and rough surfaces (Sa value of >2 μm). There is currently consensus for titanium implants that a moderately rough surface with a Sa of 1 to 2 μm has the highest osseointegration potential [82].

2.3. Clinical Application of Dental Implants and Their Survival Rates

2.3.1. Survival Rate of Alternative Implant Materials

A significant factor determining the long-term success rate of implants is peri-implant mean boss loss. According to the guidelines of the consensus report of the First European Workshop on Periodontology, successful results are achieved when bone decreases of less than 1.5 mm are noted during the first year of functional loading and 0.2 mm annual bone loss is observed [85]. Many studies have reported the success rate of dental implant materials in clinical settings. Long-term usage of titanium implants has demonstrated the material's excellent success rate in various applications [86], including single/partial implant-supported restorations, removable implant-retained/supported overdenture, and fixed implant-supported prostheses. In the past decade, zirconia implants have been employed as an alternative to titanium implants when patients have metal allergies or esthetic concerns. Zirconia has equivalent biological, physical, and biocompatibility properties to titanium [87]. In addition to material selection, several manufacturers have tried to modify the surface topography using subtractive and additive techniques to improve their properties [88].

2.3.2. Survival Rate of Dental Implants Related to Bone Density

Bone density is a significant variable for anticipating stress–strain distribution at the peri-implant area, influencing bone modeling and remodeling and, consequently, the success or failure rates of dental implants. Furthermore, the difference in stiffness between implant material and peri-implant bone causes marginal bone loss and aseptic implant loosening due to stress-shielding phenomena.

Concerning bone density, mean bone loss after implant placement determines the clinical success rate of dental implant materials.

The level of peri-implant bone loss is measured based on periapical films using the parallel technique. Regardless of the material and follow-up period, low bone quality ($D_{3/4}$) tended to have more MBL than high bone quality ($D_{1/2}$) [89][90][91][92][93][94]. For instance, the mean MBL reduction reported by Held et al. [95], at roughly 1.46 mm, is close to the borderline value recommendation (1.50 mm). However, the data suggested that the hydrophilic implants have good osseointegration characteristics even in low-quality bone. This finding is consistent with a previous systematic analysis, which found that the survival rates of dental implants depending on the bone density were type I, 97.6%; type II, 96.2%; type III, 96.5%; and type IV, 88.8%. Additionally, compared to machined surface implants, treated surface implants had a greater survival rate (97.1%) when placed in low-density bone. This higher survival rate may explain the surface treatment's role in facilitating tighter cell–titanium interactions, which enhance the bone tissue's biological and biomechanical effects [96].

3. Conclusions

- Implant material, implant design, and surgical techniques are pivotal factors affecting the success rates of dental implant placement in low-density bone.

- Both titanium and zirconia implants are widely accepted materials in the market. Nonetheless, PEEK implants serve as an alternative material for specific cases, such as those involving poor bone conditions, bruxism, and esthetic concerns.

- Modified implant topography, strengthened implant geometry, and a suitable surgical technique are selected and used to achieve high survival and success rates and attain superior clinical results.

- In low-density conditions,

  o Titanium provides a better chance of achieving initial stability due to the best mechanical performance among the three materials.

  o Conical titanium implant design, wider diameter, longer length, reverse buttress with self-tapping, small thread pitch, and deep thread depth are recommended.

  o Surgical techniques, such as underpreparation, osteotome technique, and magnetodynamic surgery, play a critical role in achieving primary stability. However, piezoelectric surgery does not affect the initial stability but does affect the secondary stability.

- Regardless of the material and follow-up period, low bone quality tended to have more marginal bone loss than high bone quality.

- Further study is required to identify an optimal implant material in terms of the bone state in clinical settings.

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