Chapter

Dental Implants

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Abstract

The goal of modern dentistry is to return patients to oral health in a predictable fashion. The partial and complete edentulous patient may be unable to recover normal function, esthetics, comfort, or speech with a traditional removable prosthesis. The patient's function when wearing a denture may be reduced to one sixth of the level formerly experienced with natural dentition; however, an implant prosthesis may return the function to near-normal limits. The esthetics of the edentulous patient is affected as a result of muscle and bone atrophy. In order to replace a missing tooth, the development of materials science and technology improved the materials for implant application. Nowadays, titanium has become the most popular implant material due to its advantages. The first submerged implant placed by Strock was still functioning 40 years later. Recently, zirconia implants and innovative surface designs are being researched and practiced. In this chapter, these materials will be comparatively discussed through contemporary literature and research.

Keywords: implant corrosion, dental implants, oral implantology, titanium implants, zirconia implants, oxide layer, zirconium dioxide, Ti-6Al-4V, calcium phosphate ceramics, osseointegration

1. Introduction

Modern dentistry aims to restore a patient's oral esthetics, contour, function, and speech. Depending on the patient's needs, the total treatment may range from treating a single tooth with caries to restoring edentulous arches with severe bone resorption.

Implant dentistry has made predictable success a reality for cases in the more difficult part of this spectrum through research, improvements in diagnostic tools, techniques, implant materials, and designs. Endosteal implants are manufactured materials inserted in edentulous ridges via surgery so they can serve as a foundation for the prosthesis [1]. Most implants that will be discussed in this chapter will be root form implants which mimic the root shape of a tooth.

1.1 History of dental implants

The desire to restore lost teeth is not a new concept. Dental implant surgery is one of the oldest practices in dentistry second only to tooth extractions. There is archeological evidence that humans have attempted to replace missing teeth with root form implants for thousands of years. Remains from ancient China dating

4000 years ago have carved bamboo pegs, tapped into the bone, to replace lost teeth, and 2000-year-old remains from ancient Egypt have similarly shaped pegs made of precious metals. Some Egyptian mummies were found to have transplanted human teeth, and in other instances, teeth made of ivory [2]. Central American Incas tapped seashells in bone similar to the Chinese [3].

In 1809, Maggiolo introduced root shaped gold implants followed by Harris introducing porcelain teeth supported by lead-coated platinum posts [4, 5]. Gold, magnesium, copper, brass, aluminum, silver, and soft steel plated with nickel and gold was used to fabricate implants by Lambotte in 1900s [6]. Corrosion of most of these metals by body tissues was observed which in return caused electrolytic action. In 1909, Greenfield introduced an implant in the form of a cylindrical lattice-cage which differed substantially from the root form implants [7]. A calibrated cylindrical bur was used for the osteotomy to preserve an inner core of bone within the implant. This was also the first design which separated the endosteal implant from the abutment which was to be connected on the implant weeks later through an internal attachment after healing. In 1940, Bothe described a titanium implant and bone interface as bone fusing [8]. The first two-piece titanium screw-type implant was designed in 1946 by Strock [9]. The direct implant-bone interface desired by Strock was called ankylosis.

Brånemark's studies in bone marrow healing in 1952 led to dental implant application in dogs in early 1960s, and implant integrations in bone were achieved without adverse reaction in surrounding tissues. Implant applications in humans with Brånemark philosophy were started in 1965, and 10-year results were published in 1977 [10]. Osseointegration, which has become the term used today for implants instead of ankylosis or bone fusing, was defined by Brånemark as a direct contact between the implant surface and living bone that can be observed through a light microscope [11].

Through advances in material sciences, manufacturing processes, research, and clinical studies, the usage of dental implants have become an essential part of contemporary restorative dentistry.

1.2 Dental implant material properties

1.2.1 Metals and alloys

Majority of the dental implants to date have been fabricated from metals and alloys. American Society for Testing and Materials and International Standards Organization have created guidelines for standardizing implant materials [12, 13].

1.2.1.1 Titanium and titanium: 6 aluminum: 4 vanadium (Ti-6Al-4V)

Titanium and its alloys are the most widely used materials for dental implants [14]. This metal group forms retentive oxides in contact with room temperature air or solutions containing oxygen such as tissue fluids. This provides an advantage since this titanium oxide surface minimizes biocorrosion. In the case of an oxide surface becoming scratched or removed during implant placement into bone, the surface reoxidizes in the bone tissue. This regenerative biocorrosion preventing layer is one of the reasons for the wide use of titanium in dental implants [15].

Bothe et al. reported bone growth in contact with titanium surfaces in rabbits [8]. Several researchers studied and expanded the indications for use of titanium in implant devices. The reason reported is titanium's non-reactive nature and its resilience to corrosion [16, 17]. General properties of alloys and metal used in implant fabrication are detailed in **Table 1** [12].

	Nominal analysis (w/o)	Modulus of elasticity GN/m^2 (psi μ 10^6)	Ultimate tensile strength MN/m^2 (ksi)	Elongation to fracture (%)
Titanium	99+Ti	97 (14)	240–550 (25–70)	>15
Titanium-aluminum-vanadium	90Ti-6Al-4V	117 (17)	869–896 (125–130)	>12
Cobalt-chromium-molybdenum (casting)	66Co-27Cr-7Mo	235 (34)	655 (95)	>8
Stainless steel (316 L)	70Fe-18Cr-12Ni	193 (28)	480–1000 (70–145)	>30
Zirconium	99+Zr	97 (14)	552 (80)	20
Tantalum	99+Ta	—	690 (100)	11
Gold	99+Au	97 (14)	207–310 (30–45)	>30
Platinum	99+Pt	166 (24)	131 (19)	40

Table 1.
Mechanical properties of various alloys and metals used in implants [13, 14].

The titanium alloy with the most widespread use is titanium-aluminum-vanadium. This alloy has approximately six times the strength of compact bone, and as a result, thinner structural parts can be incorporated into the implants without risking breakage or cracking. The alloys modulus of elasticity is 5.6 times greater than compact bone. Several studies have investigated and documented the titanium oxide layer on both pure titanium and its alloy which can vary depending on surface properties [18]. The techniques for casting titanium and alloys are limited because of high melting points and high chance of hydrogen, nitrogen, and oxygen absorption. Different purity levels can be achieved through an ultrapure protective gas environment or a high vacuum [18].

1.2.1.2 Cobalt-chromium-molybdenum-based alloy

This alloy is made up of cobalt, chromium, and molybdenum. Alloys containing cobalt are usually used as they are cast and are sometimes additionally annealed. This allows custom designs otherwise unachievable. The named elements with minor additions of nickel, manganese, and carbon provide strength four times greater than compact bone and chromium provides resistance to corrosion. These concentrations are critical so the fabrication processes must be carefully controlled and followed. Cobalt-based alloys are the least ductile of the ones used in dental implants [12]. Excellent biocompatibility has been observed with implants from cobalt-based alloys when they are manufactured properly.

1.2.1.3 Iron-chromium-nickel-based alloys

Stainless steel alloys are one of the oldest materials to be used in the medical field. The alloy is most often used in a wrought and heat treated condition, same as titanium alloys, which gives the material high strength and ductility. Among all alloys used in implant fabrication steel alloys are the ones most susceptible to biocorrosion so the applied oxide surface must be protected. Another concerning aspect of iron-based alloys are galvanic potentials. If a steel-based implant abutment

contacted a bridge containing a noble metal, for example, a circuit would be formed. This would not be a cause of concern if these units function without contact [19, 20].

1.2.1.4 Other metals and alloys

Several other metals been used in implant manufacturing. Notably, among these, gold and platinum have been evaluated but the low strength of these materials limit implant design.

1.2.2 Ceramics

Ceramics are non-metal, non-polymer, inorganic materials. Oxide ceramic dental implants were fabricated to make use of their resistance to biodegradation, strength, color, low conductivity, and elastic properties [21, 22]. Despite their low ductility and brittle nature, ceramics are being used both as coatings on other materials and in bulk form.

1.2.2.1 Aluminum, titanium, and zirconium oxides

Main properties of these materials are listed in **Table 2** [12]. High strength oxide ceramics have been used as several implant forms including root form implants [23]. Ceramics have approximately 3–5 times the strength of compact bone. Creating a different implant design for these materials is necessary because of their high strength and high modulus of elasticity. Metallic oxide ceramics generally have a white hue of color which makes them a viable option for implants in the esthetic area in cases where gingival recession leaves implants visible. When compared with other materials, minimal reactivity with oral tissues paired with low electrical and thermal conductivity are notable benefits.

As with titanium implants, bone growth directly adjacent to the implant surface has been observed. Going a step further, areas of bonding have been reported in gingival attachment zones of sapphire dental implants in animal studies [24–26]. There are also special requirements for sterilization of metallic oxide ceramic implants. Since steam and chemical solutions can lead to micro weaknesses which can lead to fractures or leftover residues; dry heat is the best choice for sterilization of ceramics. Their improved strength and excellent biocompatibility make ceramics a viable choice as an implant material.

	Modulus of elasticity GN/m^2 (psi μ 10^6)	**Ultimate bending strength MN/m^2 (ksi)**	**Elongation to fracture (%)**	**Surface**
Polycrystalline aluminum oxide	372 (54)	300–550 (43–80)	0	Al_2O_3
Single crystal aluminum oxide (sapphire)	392 (56)	640 (93)	0	Al_2O_3
Zirconium oxide zirconia (PSZ)	195–210 (28–30)	500–650 (72–94)	0	ZrO_2
Titanium oxide (titania)	280 (41)	69–103 (10–15)	0	TiO_2

Table 2.
Mechanical properties of various inert ceramics [13, 14].

1.2.2.2 Calcium phosphate ceramics (CPC)

First implants manufactured from CPCs aimed to reduce bone resorption after tooth extractions by filling the bone socket with cone-shaped implants [27]. The materials limited strength led researchers to either reinforcing the material internally with metal parts or to coat other materials with CPCs [28]. Out of these techniques, coating metal implants via flame or plasma spraying was more widely used with the intent of making metal implants more biocompatible [29].

The advantages of the application are the materials chemical similarity to living tissues, biocompatibility, and low conductivity which means it can act as a barrier to metallic ion transport between bone and metal implants. Disadvantages are its low strength and the materials possibility to dissolve or alter in time. Main properties of these materials can be found in **Table 3** [12]. Generally, bioceramics are characterized by lower hardness, strength, and elasticity modulus than ceramics like zirconia or aluminum oxide. Overall, CPCs are one of the most widely accepted, studied, and used biomaterials developed in the last decades and could find its applications expanding further as future implant surfaces as they evolve themselves through technology and research [30].

1.2.2.3 Carbon and carbon silicon compounds

Carbon and carbon silicon materials are regarded as ceramics for their non-reactive nature, but they conduct electricity and heat. Its elasticity is close to bone, and it is a biocompatible material. Clinical trials of carbon-based dental implants were carried out. Limitations in material properties, design, and applications led to clinical failures in trials which resulted in withdrawal of carbon-based materials in dental implant designs.

1.3 Influence of dental implant materials on soft and hard tissue

1.3.1 Implant surgery

Implant surgery begins with an incision on the edentulous ridge and flap elevation to expose the alveolar bone. At the end of the surgery, the same flap will be sutured and a primary wound healing of masticatory mucosa will follow. If a submerged (placed under oral mucosa level) implant is being used, a recovery surgery will be performed after a period of healing. If a non-submerged (placed on the same level as oral mucosa) implant is being used, no recovery surgery is necessary.

	Modulus of elasticity GN/m^2 (psi μ 10^6)	**Ultimate bending strength MN/m^2 (ksi)**	**Elongation to fracture (%)**	**Surface**
Hydroxyapatite	40–120 (6–17)	40–300 (6–43)	0	$Ca_{10}(PO_4)_6(OH)_2$
Tricalcium phosphate	30–120 (4–17)	15–120 (2–17)	0	$Ca_3(PO_4)_2$
Bioglass or Ceravital	40–140 (6–20)	20–350 (3–51)	0	$CaPO_4$
Carbon	25–40 (4–6)	150–250 (22–36)	0	C
Carbon-silicon (LTI)	25–40 (4–6)	200–700 (29–101)	0	CSi

Table 3.
Mechanical properties of various bioactive ceramics [13, 14].

Most implant systems available today allow creation of a recipient intrabony site for implant placement via rotary instruments. A tight fit is crucial for primary stabilization of the implant and for preventing soft tissue from penetrating the gap between the implant and the bone, effectively preventing the implant osseointegration.

Most important negative influence of the surgery stage can be creation of excessive heat with rotary instruments. It has been shown that bringing of the temperature of bone to 47°C for 1 minute is enough to kill osteogenic cells which can compromise necessary healing. As a safety measure, several sharp drills must be used at low speeds with low hand pressure and proper irrigation for cooling the site [31].

1.3.2 Long-term influences on peri-implant tissues

Following surgery if no infection or inflammatory response takes place to prevent healing, primary wound healing defines the long-term properties of surrounding tissues. Regardless of the dental implant material, the general outcome of bone healing around an implant is osseointegration which is defined by Brånemark as "a direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant [11]." Throughout several weeks of healing, woven bone which forms during early stages of healing starts to become more compact lamellar bone. This formation can be observed both from the cut bone and from the implant surface [32].

Titanium's corrosion rate in tissues is well documented [33]. In older studies, the presence of titanium has been detected in peri-implant tissues and internal organs, presumed to be caused by corrosion, mechanical wear, and peri-implant inflammation, but the compositions of the implant alloys were not strictly controlled, and in same studies, the diffusion is very slow and since titanium has little to no toxicity, it should be considered biocompatible [34, 35]. In a recent study, titanium particles have been detected in healthy and inflamed mucosa and even in patients with no titanium implants [36]. The increased amount of particles is likely the effect of the inflammation rather than its cause. Since then, higher strength alloys of titanium have emerged [37]. Recently, applications of these materials have been successful and have not resulted in significant negative effects. Titanium allergy has been studied and is known to be rare, but research is insufficient to give an accurate incidence rate [38].

The oxide surface of titanium as previously discussed exists through reacting with oxygen at normal temperatures and will rapidly reform if removed mechanically. It minimizes biocorrosion in tissues [15]. The oxide layer consists of mostly TiO_2 and to a lesser degree Ti_2O_3 and TiO [39]. While in normal temperatures, the oxide layer is less than 20 nm in thickness, when processed at high temperatures or anodized at high voltages, the layer can be 10–100 times thicker in a crystalline structure [40]. The macro and micro architecture of dental implants achieved via sand blasting, acid etching, or mechanical milling has no significant effect over the thickness of the oxide layer [41]. Naturally occurring oxidants in tissues such as hydrogen peroxide has been shown to form a complex gel with titanium on a molecular level. This layer is found to have a very low toxicity, anti-inflammatory, and bactericidal properties [42].

Coating titanium implants by hydroxyapatite via plasma spraying is a method developed to help minimize ion transfer and accelerate bone formation between the bone-implant interface [43]. The disadvantages of this coating are its possibility of partial resorption during bone remodeling, after in vivo function, or in inflammation areas [44]. A recent study tested titanium and cobalt implants coated with zirconium nitride and found the product to be cytocompatible and the red color range can potentially minimize the visibility of implants under the gingiva [45].

Aluminum oxide ceramics are used as implant bulk materials one advantage is having the oxide layer properties throughout the entire body of the implant. As a result, any removal of surface has no effect on the electrochemical properties underneath the surface. Ceramic coatings aim to give the same biocompatibility advantages to metals or alloys to be coated [46]. A systematic review including six randomized controlled trials (RCTs) studied implants consisting of 85% Ti and 15% Zr found that narrow Ti-Zr implants have comparable performance to regular diameter Ti implants noting further research is necessary [47]. Some studies tested alloys consisting of Ti-Nb and found the material to be cytocompatible and a good candidate for implantology in future research due to its very low elasticity modulus [48, 49].

1.4 Success of dental implant materials

There have been different criteria for measuring success of dental implants. The two most commonly used in literature is survival and success. Survival of an implant states whether the implant is simply still functioning in the mouth or it has been removed. Success on the other hand is concerned with the condition of peri-implant tissues and teeth as well as patients comfort and satisfaction [50].

A systematic review evaluating 23 published articles and 7711 implants over a minimum of 10 and a mean of 13.4 years found a survival rate of 94.6% and a mean bone loss of 1.3 mm around implants [51].

An article on zirconia dental implants stated zirconium dioxide is a promising alternative for titanium, but studies found significantly more early failures compared to titanium. Technical advances and innovation are found to be promising; however, there is insufficient evidence for a final verdict at present [52]. An ITI consensus report from 2018 states one-piece zirconia implants are safe in appropriate conditions but cautions against two-piece zirconia implants due to insufficient data. Same report stated that throughout different implant loading protocols and implant materials, survival rates are above 96% [53]. A meta-analysis evaluating 17 studies reviewing clinical outcomes of zirconium dioxide implants states that the survival rate was 95% over 1–7 years of follow-up [54]. A study on properties of porous tantalum found the materials similarity to bone in terms of mechanical properties and that it has less cytotoxicity than titanium. The authors claim bone growth into the implant surface to form a unique interface pattern but state tantalums safety and performance as an implant material should be further tested [55].

The lack of long-term follow-ups for zirconia implants result in researchers advising caution and stating the information in insufficient even when high survival rates are found and zirconium dioxide implants are becoming a viable alternative to metal implants.

Titanium implants in contrast have very well-documented success with follow-ups exceeding 25 years [56]. The current research in titanium implants is not concerned of success of the material but rather its viability and applications in diabetics, smokers, patients who underwent radiotherapy or anti-resorptive drugs as well as timing of implantation and loading.

1.5 Potential impacts of titanium

Titanium and its alloys have been widely and safely used in the field of oral implantology for 40 years. In the early years, researchers have argued that titanium is a bio-inert material, but with recent studies, it has been found that titanium degradation, as particle or ion release may penetrate surrounding tissues. This degradation can occur during implantation, during the prosthesis stage, or many

years after loading, during maintenance. The surface of an implant is covered with many atomic-sized titanium oxide layers for its benefit in osseointegration and corrosion resistance. Degradation of this layer over time may cause ion release from the implant surface. The compressive and frictional forces generated during osteotomy in surgical phase may disrupt this structure and cause titanium particle release. It is also possible that the biofilm formed in the abutment-implant connection, which is the weakest component of an implant, acts as a lubricant, and thus results in micro-movement and wear on the inner surface of the implant. Finally, with the exposure of the implant surface during maintenance, chemical changes may occur on the surface of the implant with factors such as saliva and bacteria. Cleaning of implants surface with various instruments may also cause titanium release [57]. Titanium release, which may occur due to the reasons listed above, has been held responsible for peri-implant diseases such as mucositis and periimplantitis in recent years. Oliviera et al. reported that titanium particles increase osteoclast activity and cause mutational changes in cells. As a result, it was argued that titanium release from the implant surface is responsible for peri-implant tissue destruction with its cytotoxic and genotoxic effect [58]. In many studies, titanium nanoparticles phagocytosed by macrophages were found in histological examination of specimens taken from the surrounding infected tissue. In a study by Wennerberg et al., implants with moderately rough surfaces emit much more titanium than other implant surfaces. The same study argues that the titanium oxide layer oscillates more easily in additive surfaces than the surfaces formed by subtraction [59]. In the light of all this information, it is not possible to say that titanium used in dental implant applications is bio-inert. Due to the surface structure of the implant, bone density, overloading, and various many different factors, potential influences in degradation of the implant surface come in sight and harmful effects on the surrounding tissues can occur [60]. On the other hand, the peripheral organ impacts of titanium are still controversial. Although it is not possible to completely eliminate the titanium particle release, there are some ways to minimize titanium release. Today, the use of different materials that are more resistant to abrasion (such as zirconium, tantalium, etc.) has come to the fore in order to protect against the possible harmful effects of titanium.

1.5.1 Implant macrogeometry

Implant macrogeometry, which can also be defined as implant design, has been one of the most researched topics in recent years. However, before examining thoroughly into this topic, it is necessary to know the two popular hypotheses that implant success and survival are based on. The first one is the "Biological Hypothesis" which declares, marginal bone loss mostly depends on bacterial plaque and the host response. "Biomechanical Hypothesis," which became a current factor, advocates the effect of occlusal excessive forces on the bone surrounding implants and compression, tension, and shear forces during and after osseointegration are crucial in implant survival and success. According to the biomechanical hypothesis, implant design is the key that provides primary stability of the implant and resistance of the implant to forces during and after osseointegration. Primary and secondary osseointegration degrees and durations of the implant have been correlated with macrogeometry in many studies. The reason for this fact is that implant macrogeometry affects the host-implant response [61]. According to these studies, the healing time of implants was shortened with the development of implant macrogeometries, and the possibility of immediate or early loading of implants came to the fore. Especially in recent years within the scope of macrogeometry, many studies have been examining implant abutment connection, implant neck

design, and their effects on long-term preservation of crestal bone. Nowadays, the aim should be to achieve an ideal implant macrogeometry to put the implants into function in the shortest time and to ensure their long-term function. The body shape, groove design, or groove geometry (groove shape, groove spacing, groove depth, groove width, implant groove surface angle, and helix angle), prosthetic interface, and implant neck design forms the macrogeometry of an implant.

1.5.2 Implant microgeometry

The concept of implant microgeometry was first described by Geng et al. in 2004 consists of implant surface topography, implant surface coating, and implant material [62]. In addition, Albrektsson et al. identified six factors for reliable osseointegration. Surface quality is one of the six factors that plays a key role in the host's response to the implant.

1.5.2.1 Implant surface topography and implant surface coating

The term implant surface refers to an outer layer of 1–2 nm which includes several outermost atomic layers different from the body material. This outermost layer is seen as the thickness of the titanium oxide layer and the structure that can be responsible for the reactions that occur on the surface. Implant surface modification can be performed in two ways by forming concave or convex surface tissue. Various methods such as sandblasting, turning, chemical and electrochemical pickling, laser application, and anodizing are used for roughening of surfaces. The amount of roughness of the resulting surface can range from nanometers to millimeters [63]. A number of studies have shown that rough surface implants have a stronger connection with bone; this structure stops the migration of epithelial attachment to the apical, thus preventing crestal bone resorption [64].

2. Conclusion

The discipline of oral implantology has come a long way from its state in 1960s. This is largely due to the rapid evolution of biomaterials discipline in 1970s. With new biomaterials and advances in surgical techniques, dental implantology is a highly successful field, consistently publishing articles reporting success rates of 90% and above over long follow-ups. Biomaterials are now manufactured and provided as sterile, standardized devices with high predictability which is essential in the field of medicine. This requirement of predictability is the reason titanium implants with widely used, well-documented surface properties are the gold standard and are the most common biomaterial of choice in dental implant devices. In recent years, zirconium implants have been rising in popularity and dependable short-term clinical outcomes look promising, but future research of long-term clinical outcomes is necessary to safely recommend and expand the indications of zirconia implants.

Conflict of interest

The authors declare no conflict of interest.

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