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## Dental Implant Biomaterials: A Comprehensive Review

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### Abstract

For the replacement of missing teeth, Dental implants have now gained popularity as one of the most significant treatment modality. In an attempt to boost the success rate of this root imitating structure, continuous efforts have been made to modify its materials and designs. To establish healthy osseointegration, biomaterials, designs and surface characteristics of implants play a key role. So, modification in these factors will aid in obtaining long-term implant stability. A wide variety of materials are available in the market and the selection of appropriate implant material is utmost important for accomplishment of successful treatment. Before choosing an implant, the clinicians should have detailed knowledge about the latest implant materials, its design aspects as well as its properties to achieve successful treatment outcome.

**Keywords:** Implant, Biomaterials, Biocompatibility, Titanium, Zirconia, Polymers.

### INTRODUCTION

With increasing success, implant dentistry has truly revolutionized the practice of dentistry for replacement of one or more missing teeth successfully. To increase the success rate, continuous attempts are being done regularly to improve the techniques, materials used and for the comprehensive understanding of bone dynamics. For the success of this treatment modality the most significant role has been played by biomaterials that are used for manufacturing implants and are brought into contact with the biological system.

In 1986, the European Society of Biomaterials defined biomaterials as “nonliving materials used for medical application (e.g., as a dental implant) with the goal of achieving a reaction (interaction) with the biologic system (Wagner 1991)”. Biomaterial has also been defined as “any substance other than a drug that can be used for any period of time as part of a system that treats, augments, or replaces any tissue, organ, or function of the body” (GPT-2005)<sup>[1]</sup>.

The most important factor for the success of dental implants is osseointegration. The concept of osseointegration was introduced by Branemark in 1952. **American Academy of Implant Dentistry** defined it as “the firm, direct and lasting biological attachment of a metallic implant to vital bone with no intervening connective tissue”<sup>[2]</sup>. So, in order to obtain desired results, an implant needs to be well osseointegrate with the adjacent bone.

Today, various biomaterials are being constructed and surface modified in an attempt to get better results. Henceforth, dentist should consider all the available information on the implant biomaterials for their judicious selection and use in Implantology. This article makes an effort to review various materials used for dental implant fabrication.

### 1. HISTORICAL PERSPECTIVE OF DENTAL IMPLANTS

The evolvement of dental implants is really an interesting story. Since the beginnings various materials have been tried for replacement of missing teeth and continuous efforts have been made to improve these materials. The brief history of dental implants is listed in Table-1.

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**Table 1:** History of dental implant <sup>[3-6]</sup>

2500 BC	Periodontally involved teeth were stabilized by Ancient Egyptians with the use of gold ligature wire.
500 BC	Etruscan population used oxen bones for replacements of teeth.
Around 300 AD	Carved ivory were used for the replacements of teeth.
600 AD	Mayan population used implants made up of pieces of shells for the replacement of teeth.
Around 800 AD	In early Honduran culture, preparation and placement of a stone implant in the mandible was reported for the first time.
1700's	John Hunter reported the possibility of transplanted teeth from one individual to another.
1789	Zirconium dioxide was accidentally identified by Martin Heinrich Klaproth.
1791	Titanium was first discovered by William Gregor and named by Martin Heinrich Klaproth in 1795.
1809	Fabrication of gold roots was done by Maggiolo.
1887	Implantation of a platinum post coated with lead by Harris.
1890	Zamenski used porcelain, gutta and rubber implants.
1898	Silver capsules in the socket were placed by RE Payne.
1900	Dental implants fabricated from various materials like alum, silver, brass, red copper, gold, magnesium, and soft steel were used by Lambotte.
1905	Scholl demonstrated a porcelain corrugated root implant.
1910	Pure titanium was first prepared by Matthew A. Hunter. It was prepared by heating $TiCl_4$ with sodium in a steel bomb at the temperature range of 700–800°C.
1913	Greenfields introduced & patented hollow 'basket' implant. This was made from the mesh work of iridium platinum wires and was soldered by using gold.
1935 to 1978	Synthetic polymers, ceramics and metal alloys were introduced.
1938	A cylindrical endosseous implant was patented by P.B.Adams.
1939	The method for the insertion of vitallium screw was presented by Drs. Alvin and Moses Strock . This screw had provided anchorage for replacement of missing teeth.
1940	Formiggini ("Father of Modern Implantology") and Zepponi developed post-type endosseous implant.
1948	Goldberg & Gershkoff reported insertion of first viable sub periosteal implant.
1952	Development of a threaded implant made up of pure titanium by Branemark.
1960	A double helical spiral implant fabricated from cobalt chromium was introduced by Chierchieve.
1969	Milton Hodosh invented polymer implants usage of metal and metal alloys, cobalt-chromium-nickel-based alloys.
1970's	Placement of vitreous carbon implants by Grenoble.
1975	Cranin <i>et al</i> conducted first research work on zirconia.
1978	The two-stage threaded root-form dental implant was introduced by Brånemark.
21 <sup>st</sup> century	Titanium implants, ceramics, aluminum, and zirconia oxide implants came into existence.
At present	Zirconia and Titanium-Zirconium alloy (Straumann Roxolid) is widely used.

## 2. CLASSIFICATION OF DENTAL IMPLANTS

In the evolution process of dental implants, numerous materials have been tried for its fabrication. The choice of material for implants application is primarily dependent on how the tissue at the implant site responds to the biochemical disturbance that a foreign material

presents i.e. biomaterial is biocompatible to oral tissues or not. The biocompatibility is a term that represents the minimal harm to the host or to the biomaterial. The most significant aspect of biocompatibility is mainly based upon the basic bulk and surface properties of biomaterials.

The classification of dental implants based on the material used and its biologic response is given in Table-2 [7].

**Table 2:** Implant materials classification based on the material used and the biologic response they exhibit [7].

Biodynamics	Chemical composition		
	Metals	Ceramics	Polymers
Biotolerant	Gold		Polyethylene
	Co-Cr alloys		Polyamide
	Stainless-Steel		Polymethylmethacrylate
	Niobium		Polytetrafluoroethylene
	Tantalum		Polyurethane
Bioinert	Commercially pure Titanium.	Aluminium oxide	
	Titanium alloy (Ti-6Al-4V)	Zirconium oxide	
Bioactive		Hydroxyapatite	
		Tricalcium phosphate	
		Calcium pyrophosphate	
		Bio glass	
		Carbon-silicon	

### 3. IMPLANT BIOMATERIALS

Since beginning numerous materials have been tried for the manufacture of dental implants. They are as following: metals and metal alloys, ceramics, carbon and carbon-silicon compounds, polymers and composites.

#### Metals and metal alloys

Metals and metal alloys are the most widely used materials in the implant fabrication. These includes titanium, tantalum, vanadium, cobalt, chromium, molybdenum and nickel etc. Despite of its wide application in the restorations, the precious metals are seldom used for implant fabrication.

#### Titanium

Due to its excellent biocompatibility, titanium is the extensively used material for implant fabrication. Many of its physical and mechanical properties make it desirable as an implant material.

There are six different types of titanium used in dentistry for the construction of dental implants. This includes four grades of

commercially pure titanium (CpTi) and two titanium alloys that are Ti-6Al-4V and Ti-6Al-4V-ELI (extra low interstitial alloy).

CpTi alloy is the mixture of titanium and oxygen. The mechanical and physical properties of CpTi differ from each other on the basis of presence of oxygen residuals in the metal. The mechanical properties of pure titanium are also enhanced by trace elements of carbon, oxygen, nitrogen and iron. These elements are present in increasing concentrations from Grade I to Grade IV. Pure titanium metals can exist as a dark gray, shiny metal or as a dark gray powder.

There are three different structural forms of titanium alloys namely alpha ( $\alpha$ ), beta ( $\beta$ ) and alpha-beta ( $\alpha + \beta$ ). The Addition of several elements such as aluminum and vanadium into the CpTi alloy can result in the formation of three phases of titanium alloys. Amongst them, the combination of  $\alpha$ - $\beta$  alloy is the extensively used alloy for manufacture of implants. It is mainly consist of 6% aluminum and 4% vanadium [8]. The composition of titanium and its alloys are enlisted in table-3. The strength of these alloys is further increased by heat treatment. The mechanical properties of commercially pure titanium and titanium alloys are listed in Table 4.

**Table 3:** Titanium grades 1–4 and Titanium alloys (Ti–6Al–4V) compositions [9].

	O(wt%)	C(wt%)	Fe(wt%)	H(wt%)	N(wt%)	Al(wt%)	V(wt%)	Ti(wt%)
CpTi, grade I	0.18	0.10	0.02	0.015	0.03	-	-	Balance
CpTi, grade II	0.25	0.10	0.03	0.015	0.03	-	-	Balance

CpTi, grade III	0.35	0.10	0.03	0.015	0.03	-	-	Balance
CpTi, grade IV	0.40	0.10	0.05	0.015	0.03	-	-	Balance
Ti-6Al-4V	0.20	0.08	0.30	0.015	0.05	5.50-6.75	3.50-4.50	Balance
Ti-6Al-4V (ELI)	0.13	0.08	0.10	0.012	0.05	5.50-6.50	3.50-4.50	Balance

In order to accelerate and improve osseointegration various methods are being used for the surface modification of the dental implants such as machining, plasma spraying, grit blasting, acid etching, alkaline

etching, anodization, laser treatment etc. Moreover, implant surface has been coated by various substances such as antibiotics, fluoride and various growth factors can also be used.

**Table 4:** Mechanical properties of commercially pure titanium and its alloys

Material	Modulus (Gpa)	Ultimate Tensile strength(Mpa)	Yield Strength(Mpa)	Elongation (%)	Density	Type of alloy
CpTi, grade I	102	240	170	24	4.5	A
CpTi, grade II	102	345	275	20	4.5	A
CpTi, grade III	102	450	380	18	4.5	A
CpTi, grade IV	104	550	483	15	4.5	A
Ti-6Al-4V- ELI	113	860	795	10	4.4	$\alpha + \beta$
Ti-6Al-4V	113	930	860	10	4.4	$\alpha + \beta$
Ti-6Al-7Nb	114	900-1050	880-950	8-15	4.4	$\alpha + \beta$
Ti-5Al-2.5Fe	112	1020	895	15	4.4	$\alpha + \beta$
Ti-15Zr-4Nb-2Ta-0.2Pd	94-99	715-919	693-806	18-28	4.4	$\alpha + \beta$
Ti-29Nb-13Ta-4.6Zr	80	911	864	13.2	4.4	$\alpha + \beta$

Adopted from: Lemons, 1990<sup>[10]</sup>, Craig, 1993<sup>[11]</sup>, Wataha, 1996<sup>[12]</sup>, McCracken, 1999<sup>[13]</sup>

Recently, the addition of various elements such as Zirconium, Niobium, and Tantalum to the alloy has shown no toxicity or any deleterious tissue reactions and displays a better corrosion resistance<sup>[14]</sup>. Recently, a new alloy Roxolid has come into the picture for the construction of narrow diameter implants. It was developed by **Straumann** consisted of superior mechanical properties such as increased fatigue strength and elongation than the pure titanium, thereby satisfying all the criteria of dental implantologists and accounting for being 50% much stronger than the titanium<sup>[15]</sup>.

However, its major drawback is its dark gray color which shines through the peri-implant mucosa which proves to be an esthetic concern for the patients. Extensive research to solve the problems related to esthetics leads to the discovery of tooth-colored implants and thus, zirconia came into existence<sup>[9]</sup>.

#### Cobalt-Chromium-Molybdenum-based alloys:

These alloys are often used in cast or cast and annealed metallurgical states. Which enables them to be used in the construction of custom designed implants such as subperiosteal frames. This alloy contains 63% Cobalt, 30% Chromium and 5% Molybdenum. Chromium provides corrosion resistance, while molybdenum provides strength and bulk corrosion resistance. However, this alloy is not as resistant to corrosion as titanium.

#### Iron-Chromium-Nickel-based alloys:

This alloy is basically the surgical steel or austenitic steel. Since long, it has been used in the construction of orthopedic devices and dental implants. This alloy is mainly comprised of iron, chromium – 18% and nickel – 8%.

This alloy exhibits high strength and high ductility when combined with titanium systems. This alloy is most commonly used in fabrication of ramus blade, ramus frame, stabilizer pins and some mucosal insert systems. Although this alloy possesses high mechanical strength and is cheaper; its corrosion properties are inferior to titanium. This make its usage limited as an implant material.

#### Precious Metals

Various precious metals like tantalum, platinum, indium, gold, palladium, and alloys of these metals have also been used as dental implant biomaterial.

In the past, gold was used as dental implant material. It possesses several benefits like corrosion resistance and good biocompatibility. However, it is precluded from being used as implant biomaterial due to some limitations like high cost and lower mechanical strength<sup>[8]</sup>.

#### A) Ceramics

Various ceramics used as dental implant materials are: aluminum oxide, zirconia, hydroxapatite, calcium phosphate, bioglass etc.

#### Aluminium oxide (Al<sub>2</sub>O<sub>3</sub>):

Due to its bioinert nature, it is considered as excellent biomaterial for ceramic dental implants. Aluminium oxide ( $Al_2O_3$ ) dental implants demonstrated good osseointegration but due to its poor survival rate it has withdrawn from the market. Due to its excellent corrosion resistance, good compatibility, high wear resistance and high strength, it has been considered as implant biomaterial.

**Calcium phosphate ceramic:**

It is non-immunogenic and biocompatible with host tissues. Hydroxyapatite and Tricalcium phosphate are the two most commonly used calcium phosphates. Due to their ability to establish direct bond between implant and bone, they are often used as grafting material to facilitate new bone formation.

Regardless of its use as a bone substitute, they have also been considered as a standard option for implant coatings in order to accelerate bone healing surrounding the implants. However, other studies indicated that there is no remarkable difference between coated & uncoated implants after months of integration, which implies early integration, may be quite different.

**Bioglass ( $SiO_2$ -CaO-Na<sub>2</sub>O-P<sub>2</sub>O<sub>5</sub>-MgO):**

Bioglass is another ceramic material that is classified as bioactive as it accelerates formation of bone. Despite their favorable osteoinductive ability, it is very brittle in nature which limits its use in some stress bearing areas. This material is used more commonly as a graft material in the cases of ridge defects or other bone defects than as a coating material of the implants [16].

**Zirconia:**

**Table 5:** Mechanical properties of zirconia ceramics [8]

Material	Chemical composition	Modulus (GPa)	Fracture toughness (MPa m <sup>-1</sup> )	Flexural strength (MPa)	Density (g/cc)	Color
3Y-TZP	98% small equiaxed tetragonal grains of zirconia (ZrO <sub>2</sub> )+3 mol% yttria (Y <sub>2</sub> O <sub>3</sub> )	210 GPa	7-10 MPa m <sup>-1</sup>	800 to 1,000 MPa	6 g/cc	Ivory
ZTA	33 vol% of 12 mol% ceria-stabilized zirconia (12Ce-TZP) to In-Ceram alumina	285 GPa	5-6 MPa m <sup>-1</sup>	1422±60 MPa	5 g/cc	White
ATZ	20 wt% alumina+80 wt% zirconia containing 3 mol% yttria	260 GPa	5-6 MPa m <sup>-1</sup>	1800-2,400 MPa	5.45±0.02 g/cc	White/ Off-white

Recently, the ceramics blocks are fabricated by addition of alumina to 3Y-TZP, which are known as TZP-A. The addition of alumina will help in improving the durability as well as the stability under high temperatures and humid environments. However, this has been at the expense of the reduced translucency of ceramic blocks.

Ceramics as a dental implant material has many benefits like they are inert to biodegradation possess high strength and other physical properties which make them suitable for application in Implantology. On the other hand, there are several drawbacks associated with these materials are low ductility and brittle nature; therefore handling of this material requires special care, which has limited its application as a dental implant material.

The presence of high compressive, tensile and bending strengths, high modulus of elasticity, with fatigue and fracture strength have limited these biomaterials for special design needs only [8].

The word zirconium was derived from the arabic word “zargon” meaning golden in color. This material was first introduced in dentistry in the early 1990s for clinical applications such as frameworks for all ceramic crowns and fixed partial dentures and abutments. First research on zirconia was published by **Cranin et al** in 1975.

At room temperature, unalloyed zirconia can be seen in three different forms on the basis of amount of temperature used:

- At room temperature and upon heating up to 1170° C, it exist in the monoclinic form
- Heating it between 1170° C and 2370° C will give tetragonal form.
- Heating it beyond 2370° C and up to its melting point will give Cubic form.

Although, there is the availability of different types of zirconia ceramics, only three types have been used for the dental application. These are [17].

- Yttrium stabilized zirconia polycrystals (tetragonal zirconia polycrystals 3Y-TZP).
- Transformation toughened partially stabilized zirconia with magnesium (Mg-PSZ).
- Dispersion toughened ceramics - zirconia toughened alumina (ZTA).

The TZP is the type of zirconia which contains tetragonal phase only. At room temperature, addition of yttrium aids in obtaining TZP. 3Y-TZP is the standard material for the biomedical application as it exhibits low porosity, high density, compression strength and high bending. Mechanical Properties of zirconia ceramics is listed in table 5.

**B) Carbon and carbon silicon compounds**

The carbon is an element, which is available in several forms. In the year of 1970, the use of carbon and carbon silicon compounds were first reported in Implant Dentistry. Due to its good biocompatibility and resemblance of mechanical properties to the bone tissue, it can be considered as better option for orthopedic implants. In comparison with the other materials, these materials do not suffer from fatigue. However, its low tensile strength and brittle nature have limited its use in major load bearing areas only [18].

**D) Polymers and Composites**

The use of polymers as implant biomaterials was first reported in 1930s. During that time the polymers that were used are Polymethyl methacrylate (PMMA) and Polytetrafluoroethylene (PTFE). Other types of polymers, which were used afterwards as implant material included polyamide, polyethylene (PE), polyurethane (PU), polypropylene (PP), polydimethylsiloxane, polysulfone (PS) and silicone. As compared with

the other biomaterials, the polymeric implants possess lower strengths, elastic moduli and higher elongation to fracture. Most polymers exhibit presence of elastic modulus almost similar to the soft tissues.

In certain instances, combination of biodegradable polymers like polyvinylalcohol, polylactides, polyglycosides, cyanoacrylates or other forms and biodegradable CaPO<sub>4</sub> are prepared to be used as structured scaffolds, plates, screws etc <sup>[8]</sup>.

Recently, a new addition to polymers being used for the dental implant fabrication is polyether ether ketone (PEEK). The main benefit of this material over other materials like titanium and zirconium is its elastic modulus (3.6 Gpa), which is closer to bone. Additionally, this material is being reinforced with carbon fiber so as to achieve a modulus of elasticity of 17.4 Gpa, which is close to cortical bone. Moreover, this material possesses better aesthetic properties and it is suitable in patients who are allergic to titanium <sup>[19]</sup>.

#### 4. GUIDELINES FOR SELECTING IMPLANT BIOMATERIAL <sup>[16]</sup>

The ADA has given some guidelines for selection of implants biomaterials:

- Evaluation of physical properties that ensure sufficient strength
- It should be easy to fabricate and capable of being sterilized without getting degraded.
- Evaluation of safety and biocompatibility, including cytotoxicity testing & tissue interference characteristics.
- Freedom from defects.
- At least two independent longitudinal clinical studies presenting its efficacy.

#### 5. CURRENT TRENDS

The introduction of nanotechnology has opened a new door in the field of implant dentistry. In recent years, advent of nanostructured materials such as polymer nano composites has provided us the opportunity for the development of computer model designed new implant materials with pre determined shapes and porosities. Although, it is not yet clear that nanopatterning is considerably better than micron patterning. Despite of this, surface coatings by different materials has improved its properties and enabled it to be used in the compromised treatment sites to enhance treatment outcomes <sup>[20]</sup>.

#### CONCLUSION

As dental implants have been gaining popularity day by day amongst the patients; continuous efforts have been made in modifications of dental implant materials and designs. The implant materials, implant designs and its surface characteristics are the major factors which can influence the success of the dental implant. So, modification in these factors will aid into successful treatment outcome and long-term implant stability. Since long titanium and titanium alloys have been most frequently used materials due to their excellent biocompatibility and superior mechanical properties. Zirconia-based ceramics have higher biocompatibility and better aesthetics than titanium-based alloys; on the contrary titanium-based implants have shown to have significantly better mechanical properties, longer history of application and therefore, achieved reliability over time. Thus, zirconia stands is known to have a promising future in upcoming years. So, to improve the quality of treatment provided to patients, further researches are needed to improve the properties of implant biomaterials and to consider other materials as feasible alternative of titanium and zirconia.

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#### Conflict of Interest

The authors declare no conflict of interest.

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