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Review

Titanium Alloys for Dental Implants: A Review

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Abstract: The topic of titanium alloys for dental implants has been reviewed. The basis of the review was a search using PubMed, with the large number of references identified being reduced to a manageable number by concentrating on more recent articles and reports of biocompatibility and of implant durability. Implants made mainly from titanium have been used for the fabrication of dental implants since around 1981. The main alloys are so-called commercially pure titanium (cpTi) and Ti-6Al-4V, both of which give clinical success rates of up to 99% at 10 years. Both alloys are biocompatible in contact with bone and the gingival tissues, and are capable of undergoing osseointegration. Investigations of novel titanium alloys developed for orthopaedics show that they offer few advantages as dental implants. The main findings of this review are that the alloys cpTi and Ti-6Al-4V are highly satisfactory materials, and that there is little scope for improvement as far as dentistry is concerned. The conclusion is that these materials will continue to be used for dental implants well into the foreseeable future.

Keywords: titanium; alloys; dentistry; corrosion; biocompatibility; osseointegration; clinical outcomes

1. Introduction

The topic of titanium alloys for use as dental implants has been studied. A search was carried out through PubMed based on the key words *titanium*, *dental* and *alloys*, with further refinements through the keywords *osseointegration*, *biocompatibility*, *corrosion* and *novel alloys*. This gave an initial number of 7700 references, and even following the refinements, there were several hundred relevant references identified. The main selection from these was to concentrate on papers published in the past five years, with an emphasis on experimental studies of biological properties and on reviews of clinical performance. Key papers published before this have been included where they provide information on current practice and illustrate how the clinical use of titanium-based implants has evolved.

2. Titanium-Based Dental Implants

Since the introduction of titanium alloys for the purpose around 1981, there has been a marked increase in the use of dental implants to replace lost teeth in patients [1,2]. The most common reason for tooth loss in adults is periodontal disease, though other causes, such as trauma and developmental defects, may also lead to it [1]. Modern titanium-based dental implants have high success rates and are only rarely associated with complications or failure [1].

Implants involve the use of a metal support that is in direct contact with the bone. Titanium is used in alloys to fabricate dental implants due to its good mechanical properties, low density (4.5 g/cm^3) and good bone-contact biocompatibility. The main alloy used is so-called commercially pure titanium, cpTi [3]. This metal is available in four grades numbered 1 to 4, according to the purity and the processing oxygen content [4]. These grades differ in corrosion resistance, ductility and strength, and it is grade 4 cp-Ti, with the highest oxygen content (around 0.4%) and best overall mechanical strength

(see Table 1), that is most widely used for dental implants [4,5]. There is also the alloy Ti-6Al-4V, sometimes called grade 5 titanium. Its composition is also shown in Table 1, where it can be seen that the numbers in the formula refer to the approximate percentage composition by mass.

Grade 5 titanium is widely used in orthopaedics [6,7]. This is because of its superior strength and lower Young's modulus. However, it may also be used in dentistry, and the use of this alloy has been shown to be acceptable biologically [7]. However, this alloy releases both aluminium and vanadium [7], both of which are capable of causing biological problems. Aluminium interferes with bone mineralization [8], leading to structural deficiencies, and vanadium is both cytotoxic and capable of causing type IV (allergic) reactions [9]. To have these adverse effects, they both need to be present in the tissues at reasonable concentrations, and levels released from this alloy are well below those needed to produce toxic effects [7]. Amounts released are also below the average nutritional uptake of these ions. Studies have confirmed that this alloy will undergo satisfactory osseointegration [3–5], especially when treated to enhance the oxide layer on the surface [10].

Table 1. Composition and properties of titanium alloys used as implants.

	cpTi Grade 1	**cpTi Grade 2**	**cpTi Grade 3**	**cpTi Grade 4**	**Ti6Al4V**
Titanium	ca 99%	ca 99%	ca 99%	ca 99%	90%
Oxygen	0.18%	0.25%	0.35%	0.4%	0.2% max
Iron	0.2%	0.2%	0.2%	0.3%	0.25%
Nitrogen	0.03%	0.03%	0.05%	0.05%	-
Hydrogen	0.15%	0.15%	0.15%	0.15%	-
Carbon	0.1%	0.1%	0.1%	0.1%	-
UTS/MPa	240	340	450	550	900
Yield					
strength/MPa	170	275	380	480	850
Elongation at failure/%	25	20	18	15	10

The design of modern implants usually involves a screw thread through which the metal alloy component becomes anchored within the bone of the mandible or maxilla. A smooth section of metal protrudes through the soft tissue of the gingiva and supports the artificial tooth, which is typically made from a ceramic material [11,12]. Partly as a result of this design, care has to be taken in selecting the patient to receive an implant. There has to be enough bone in the affected part of the mandible or maxilla to secure and support the implant [13], and the site must also have a good supply of blood. This means that the patient must be free of circulatory disorders, and should also be a non-smoker. This latter factor is important because tobacco smoke has the effect of making the blood capillaries to contract, causing them to reduce the blood supply to the soft tissues [14]. Lastly, patients have to maintain good levels of oral hygiene. This is to reduce the possibility of infection in the tissues adjacent to the implant [15].

When implants are used in dentistry, they should be handled carefully to make sure that they do not become contaminated. The surfaces should be kept scrupulously clean and, in order to achieve this, precautions are advised, such as manipulating the implant with titanium-tipped forceps and avoiding touching any of the surfaces [16]. Despite these precautions, surface analysis using X-ray photoelectron spectroscopy (XPS) and time-of-flight secondary ion mass spectrometry (ToF SIMS) has shown that surfaces attract considerable amounts of contamination during handling [17]. This contamination is typically organic, and shows high levels of carbon with some oxygen. Detecting titanium in these surfaces was often not possible [17]. However, despite this, the long-term integrity of titanium implants and their ability to osseointegrate are good. Survival rates of at least 89% over 10 years have been reported, and figures have typically exceeded this figure by considerable amounts. These studies have involved several hundred implants, with survival rates in the range 97–99% [18–22] (Table 2) showing just how successful these devices are.

Table 2. Recent clinical outcomes of titanium-based dental implants.

Follow-Up Time/Years	Pretreatment	Survival Rate/%	Reference
10	Sandblast and acid-etch	98.8	[13]
10	Sandblast and acid-etch	99.7	[14]
20	Plasma-sprayed with Ti	89.5	[15]
10	Anodised	96.5	[16]
9–12	Oxidised	97.1	[17]

Another possible source of contamination that should be considered is bacterial contamination during surgical placement of the dental implant [23]. This type of contamination can occur when bacteria that are present naturally within the oral tissues colonise the sub-gingival surface of the implant. This may then lead to infection and impairment of the healing process, with the process of osseointegration being compromised [24]. A systematic review [23] considered this topic and addressed the question of whether such contamination influences the success of dental implants to any great extent, but concluded that there was insufficient evidence to draw firm conclusions.

2.1. Titanium and its Alloys

Titanium is a transition metal that is able to form solid solutions with elements with similarly sized atoms. In the solid state, it has hexagonal close packed geometry up to 882.5 °C, known as the α structure. Above this temperature, solid titanium changes to a body centred cubic form known as the β structure, until it melts at 1688 °C [25]. In alloys, titanium occurs in a variety of forms, which can be pure α or pure β, or combinations of the two [26]. The alloying elements with titanium are either α-stabilisers, such aluminium, or β-stabilisers, such as vanadium, iron, nickel and cobalt. Oxygen is an α-stabiliser. There are also a few metallic elements, such as zirconium, which have no influence on the stability of either the phases.

In making implants, titanium alloys that are either completely or mainly α are preferred, because they have superior corrosion resistance. The processing conditions can be selected to favour the α micro-structure, and this also affects the mechanical properties (strength, ductility, fatigue resistance and fracture toughness). Data on phase structures of titanium alloys and their physical properties are given in Table 3.

Table 3. Properties of alloys of titanium for dental implants.

Alloy	Micro-Structure	Elastic Modulus/GPa	Yield Strength/MPa	Density/g cm^{-3}
cpTi Grade 1	α	102	170	4.5
cpTi Grade 2	α	102	275	4.5
cpTi Grade 3	α	102	380	4.5
cpTi Grade 4	α	104	483	4.5
Ti-6A1-4V	α + β	113	795	4.4

2.2. Surface Chemistry

For both of the main alloys used to make implantable devices, namely commercially pure titanium, cpTi, and Ti-6A1-4V, the surfaces are mainly composed of the oxide TiO_2 [27]. This oxide layer is 4–6 nm thick and also contains hydroxyl groups in addition to the oxide. The exact composition of the surface is important in promoting the adhesion of osteoblasts and the oxide layer tends to have favourable biological properties. However, the body still recognizes it as a foreign body, so that under some circumstances it may cause fibrosis to develop around the implant [28].

The detailed structure of the TiO_2 film on titanium surfaces varies with the composition of the alloy, and also with its processing history (see Table 4). Titanium implants usually have their surfaces modified after their initial fabrication in order to ensure that oxidation is uniform and that any contamination is removed [29]. The resulting surfaces have improved biological characteristics, and promote the processes of cell adhesion and proliferation, both of which contribute to bone bonding [30,31].

Table 4. Possible surface treatments of titanium alloy implants.

Treatment type	Surface Change	Effect
Mechanical		
Machining	Alter surface roughness.	Cleans surface.
Grinding		Improves adhesion
Polishing		
Blasting		
Chemical		
Acid treatment	Modifies oxide layer.	Improves biocompatibility in all cases.
Alkali treatment	Forms sodium titanate gel.	Improves biocompatibility in all cases.
Hydrogen peroxide	Dense inner oxide layer, porous outer layer.	
Anodic oxidation	Increase thickness of TiO_2	
Physical		
Plasma spray	Deposits coating such as hydroxyapatite.	
Flame spray	Deposits coating such as hydroxyapatite.	Improves wear and corrosion resistance.
Ion beam implantation	Modifies surface composition.	Enhances biological properties.

The surface of the alloy Ti-6A1-4V has quite a different composition from those of the various grades of cpTi [28]. As well as TiO_2, this alloy contains both aluminium and vanadium in the surface layers, usually as the appropriate metal oxides. This alters the metal–cell interactions, and is why dental implants are more often made from cpTi.

The surface finish and roughness are also important features of titanium implants because they influence the quality of the interaction with the bone. Surface roughness can be quantified by the terms S_a, the arithmetic mean of the roughness area from the mean plane, and S_{ds}, the density of peaks per unit of area [32]. Surfaces of implants can be divided into four different categories, depending on the surface roughness based on the value of S_a as follows: smooth (S_a < 0.5 μm); minimally rough (S_a between 0.5–1.0 μm); moderately rough (S_a between 1.0–2.0 μm); rough (S_a > 2.0 μm) [33]. In general, it is moderately rough surfaces that give the best results [34,35].

3. Biocompatibility of Titanium for Dental Implants

Corrosion behaviour is one of the most important factors that influence the biocompatibility of metal implants. This is because the metal ions that corrosion liberates can cause various adverse effects. These can be both to the tissue immediately surrounding the implant and systemically, where there may be allergic reactions. The latter, so called type IV reactions, do not depend on the dose, so are not affected by the rate of corrosion. They occur simply because corrosion causes metal ions to be released.

On the other hand, tissue reactions adjacent to the implant do depend on the dose, so that in turn, they are affected by the rate of corrosion. Titanium alloys have good corrosion resistance [36], though this may be altered by the presence of proteins such as albumin, and consequently there can be

an increase in the amount of titanium released into the tissues [37]. Evaluating how much titanium might be released and how damaging it might be is difficult, because a number of different animal models have been used in the published studies, and also different approaches to implantation and implant retrieval have been used. In some animals, e.g., baboons and rabbits, titanium levels in the tissues did not change when implants were present [38], whereas in other animals, e.g., rats, elevated concentrations of titanium were found in the spleen and there was observable degeneration of the liver [38].

The two most widely used titanium alloys, cpTi and Ti-6A1-4V can both readily osseointegrate. Osseointegration is considered to occur when direct contact develops between the living bone and the metal, without any intervening layer of fibrous capsule. Both cpTi and Ti-6A1-4V are bioactive and able to promote the formation of bone in direct contact with the metal surface. This is different from the biomedical alloys 316L stainless steel and cobalt-chromium, where living bone is unable to make close contact with the metal surface.

The interfacial zone between the titanium alloy implant and living bone is critical in the development of osseointegration. This region, which is thin (20–50 nm), is the region into which growth factors are released from the bone cells, and this initiates the steps that result in bone formation [39]. The initial step is deposition of proteins from the blood plasma onto the surface oxide layer. This is followed by the formation of a fibrin matrix, a structure that acts as a scaffold for osteoblasts (the bone-forming cells) [40]. Supported in this way, the osteoblasts lay down bone, which expands to fill the interfacial region, so that it grows right up against the implant surface, causing the implant to become osseointegrated. The important effect of proper osseointegration is that the implant is held rigidly, unlike the case where fibrous capsule forms, and in dentistry this provides a firm anchor for the prosthetic device.

The oxide layer on the surface plays a major role in the success of osseointegration. Thicker and rougher oxide coatings encourage osseointegration to occur reliably and quickly, at least over the shorter term [41,42]. The oxide coating also has the effect of passivating the metal, so that corrosion is inhibited and the release of titanium ions is minimized [43].

Cells of various types interact with the surfaces of titanium alloys. These alloys have surfaces with the appropriate surface energy and charge, and the first thing they do is to attract a layer of proteins [44]. A sequence of proteins is deposited, eventually leading to the deposition of extracellular matrix proteins [44], and these stimulate the osteoblasts, which then become attached [45]. As has already been mentioned, cells prefer rough, porous surfaces with an irregular morphology [34,35,46], of the type that can be readily produced on implantable devices.

When dental implants are used, titanium levels in the blood [47] and the serum [48,49] are raised. The increases are minor but significant, and indicate that titanium is leached from these devices. Entering the blood stream indicates that the titanium released is capable of being transported round the whole body. However, in most patients, it has no toxic effects on any of the body's tissues [50]. In a very small number, there may be adverse systemic effects in the form of type IV reactions [50,51]. However, these are very rare and affect only a very small number of patients. In most patients, titanium is completely acceptable within the body and its presence causes no adverse effects.

The widely used alloys cpTi and Ti-6Al-4V have excellent properties for use as dental implants. There has been discussion in the literature as to which is better for use as dental implants [52]. Generally, cpTi is slightly favoured [53], but results of in vitro studies have usually found that Ti-6Al-4V is superior. What can be said of both alloys is that they undergo osseointegration and are highly biocompatible with bone and oral tissues. They show minimal corrosion and cause few systematic effects in a small minority of patients. Biomechanically they are fit for purpose and clinical survival rates are high over many years of service. Consequently, the scope for improving them is slight. Nevertheless, there has been some interest in developing new alloys for use as dental implants. The main approach has been to eliminate the elements with the potential to cause harm biologically, mainly vanadium, and to reduce

the modulus so that it more closely matches that of bone [4]. The various approaches that have been tried are considered in the remaining sections of this paper.

In order for an alloy to be considered biocompatible and for it to undergo osseointegration, it must be tested in a variety of ways. One important preliminary test is for cytotoxicity. Like most metals, titanium alloys in the bulk are not toxic, but when they corrode and form ions, or wear and generate particles, they may become so [54]. In order to measure the cytotoxicity of metal ions or wear debris, the standard method is the MTT assay, as described in the appropriate International Standard for the biological evaluation of medical devices [55].

The test procedure involves a colorimetric test for mitochondrial activity of cultured cells using the reagent MTT (3-(4,5-dimethylthiazol-2-yl diphenyltetrazolium bromide). When cells have active mitochondria, they reduce MTT to a formazan that is both insoluble and strongly coloured [56,57]. The colour that develops, a deep purple, has a maximum absorbance at a wavelength of 570 nm and measuring the absorbance at this wavelength enables the number of viable cells in a sample to be quantified directly [56,57].

MTT assays are typically carried out in 96-well plates, which allows high throughput. The reagent is dissolved in physiologically balanced solutions and added to cells in culture, typically at concentrations in the range 0.2 to 0.5 mg/cm^3. They are incubated for short periods of time (1–4 hours), then the amount of the purple formazan produced is determined from absorbance measurements at 570 nm in a calibrated colorimeter. Healthy cells with high mitochondrial activity produce the deepest purple colour [56,57].

Testing in this way has been carried out on numerous titanium alloys in order to determine their cytotoxicity [58–61]. For example, Ti-6Al-4V has been shown to have cytotoxicity comparable to that of pure titanium metal, despite the presence of both aluminium and vanadium [58]. Other alloying elements have also been shown to be acceptable using the MTT assay, including iron [58], molybdenum [58,62], niobium [58,62], zirconium [63] and tantalum [63]. Copper, by contrast, has been found to increase the cytotoxicity markedly [59]. Studies have confirmed that low cytotoxicity correlates with cells being able to adhere to metal surfaces and remain functional [64]. Low cytotoxicity is thus the foundation of the other desirable biological properties of titanium alloys, namely biocompatibility and osseointegration.

4. Binary Alloys of Titanium

A large number of metals have been alloyed with titanium, typically as the minor component, to prepare alloys for possible use as dental implants. These include niobium [58,65–68], silver [68,69], gold [70], manganese [71] and zirconium [63,72–74]. Some alloying elements, such as silver or chromium [75] probably reduce the biocompatibility of the alloy. This is because they are likely to release either silver or chromium, both of which are known to have adverse biological effects [76,77]. On the other hand, several of the elements used, such as niobium [58] and zirconium [63], are benign in terms of their biological effects, so the resulting alloys are more promising for use as implant materials.

A considerable amount of work has been done on binary alloys of titanium with zirconium. These have varied widely in composition, from 10% by mass zirconium [78], to up to 50% by mass zirconium [79] and, in one study, 70% by mass zirconium [75]. Zirconium has a number of advantages as alloying metal for this application. It readily forms alloys with titanium, and it strongly resists corrosion [78], which means that it releases only trace amounts of metal ions into the body. Despite this, Ti-Zr alloys show inferior osseointegration with living bone [79]. On the other hand, studies aimed specifically at dental applications have shown the alloys to have mechanical properties comparable with cpTi [80], and, with suitable surface preparation, good biocompatibility and improved osteoblast adhesion compared with cpTi [81]. Both of these findings suggest that Ti-Zr alloys may have some advantages when used for dental implants.

Niobium has also been studied in binary alloys with titanium [82], though it has been more widely used in ternary alloys, such as Ti-6Al-7Nb [26]. Binary alloys containing minor amounts of niobium

(less than 10% by mass) have been found to have good mechanical properties. Their hardness, yield strengths and tensile strengths typically exceed those of cpTi [83]. There is also evidence that their corrosion behaviour is improved [66]. Despite this improvement, experimental studies have shown that human fibroblasts grow slower and less extensively in Ti-Nb alloys than on cpTi [84].

Manganese is an element that is generally acceptable biologically [4], and for that reason it has been studied in binary alloys with titanium. Levels have been relatively low, i.e., 8% or 12% by mass, and the effects have been beneficial. Hardness and density both increase when manganese is present [71]. Cell adhesion appears to be enhanced in the alloy [85], but cell viability adjacent to these alloys was slightly inferior that that around a cpTi implant [71].

The noble metals silver [53], gold [86], platinum and palladium [87] have been used to prepare binary biomedical alloys with titanium. Not surprisingly, these alloys were all found to have improved corrosion resistance compared with cpTi, so might be expected to show superior biocompatibility with bone and soft tissues [53,83,84]. However, this has only been confirmed experimentally for the Ti-Ag system [87]. Such alloys are inevitably expensive [88], and it is doubtful whether the marginal improvement in corrosion resistance justifies their high cost.

There have been some studies reported on binary alloys of indium with titanium [89,90]. Like zirconium, indium has also been used in multi-component alloys, such as Ti-In-Nb-Ta, where the alloy showed good bioactivity [91]. In binary alloys, indium imparted increased strength and also corrosion resistance that was at least as good as cpTi [90]. This, in turn, led to the alloy having good biocompatibility in cell cultures.

So far, these studies of binary alloys suggest that there are several possible pairings with titanium that are less susceptible to corrosion, and because of this, show greater biocompatibility with cells. However, the only binary alloy that has really been offered substantial improvements so far is Ti-Zr, and there are ongoing studies on this material as a possible alloy for fabricating dental implants.

5. Multi-Component Alloys of Titanium

A range of alloys containing at least three metals has been studied as possible implant materials, including for dentistry. They are listed in Table 5. The additional components are typically transition metals, though tin has also been included in a few experimental studies. In some instances, changes in composition resulted in the inclusion of additional amounts of oxygen [92], though the oxygen concentration has not typically been affected by changes in metal composition.

Table 5. Multi-component alloys studied as implant materials.

Composition	Reference	Reference Number
Ti-15Zr-4Nb-0.2Pd-0.2O-0.05N	Okazaki et al, *Biomaterials*, **1998**, *19*, 1197.	[92]
Ti-15Zr-4Nb-4Ta-4Mo	Okazaki et al, *Biomaterials*, **1998**, *19*, 1197.	[92]
Ti-16Nb-13Ta-4Mo	Niinomi, et al, *Mater. Sci. Eng. A.*, **1999**, *263*, 193.	[93]
Ti-15Sn-4Nb-2Ta-0.2Pd	Okazaki et al, *Biomaterials*, **1998**, *19*, 1197.	[92]
Ti-15Sn-4Nb-0.2Pd-0.2O	Okazaki et al, *Biomaterials*, **1998**, *19*, 1197.	[92]
Ti-15Zr-10Cr	Wang et al, *Mater. Sci. Eng. C.*, **2015**, *51*, 148.	[94]
Ti-13Nb-13Zr	Correa et al, *Mater. Sci. Eng. C.*, **2014**, *34*, 354.	[95]
Ti-29Nb-13Ta-4Mo	Niinomi et al, *Mater. Sci. Eng. A.*, **1999**, *263*, 193.	[93]
Ti-29Nb-13Ta-6Sn	Niinomi et al, *Mater. Sci. Eng. A.*, **1999**, *263*, 193.	[93]
Ti-29Nb-13Ta-2Sn	Niinomi et al, *Mater. Sci. Eng. A.*, **1999**, *263*, 193.	[93]
Ti-19Zr-10Nb-1Fe	Xue et al, *Mater. Sci. Eng. C.*, **2015**, *50*, 179–186.	[96]
Ti-29Nb-13Ta	Raducanu et al, *J. Mech. Behav. Biomed. Mater.*, **2011**, *4*, 1421.	[97]
Ti-29Nb-13Ta-7Zr	Correa et al, *Mater. Sci. Eng. C.*, **2014**, *34*, 354.	[95]
Ti-10Zr-5Nb-5Ta	Raducanu et al, *J. Mech. Behav. Biomed. Mater.*, **2011**, *4*, 1421.	[97]

Elements, such as tin, iron and palladium, have been used only in a relatively few studies, whereas others, such as zirconium, niobium and tantalum, have been studied by several groups of workers and results with them appear in a number of publications. Niobium and tantalum both stabilize the β phase of titanium [26,27], so their presence effectively replaces vanadium in Ti-6Al-4V and in the case of either metal, does so with an improvement in the biological acceptability of the resulting alloy. Alloys that are fabricated with niobium and/or tantalum contain both the α and β phases. The presence of the β phase is particularly desirable in biomedical grades of titanium because it confers low elastic modulus and increased corrosion resistance [93,96], both of which result in superior performance.

One multi-component alloy of titanium with niobium that has been widely studied for bone-contact applications is Ti-6Al-7Nb. In particular, it has become increasingly used to fabricate dental implants [98–100]. It is an α-β alloy and was originally developed for orthopaedics, and has superior mechanical properties compared with cpTi [101]. It is also resistant to corrosion [102] and when corrosion does occur, its biological properties are acceptable, mainly because of the absence of vanadium [103,104].

In terms of the biological responses it evokes, Ti-6Al-7Nb resembles cpTi. Human gingival fibroblasts have been found to adhere, spread and proliferate to similar extents on both alloys [105]. Short-term implantation of Ti-6Al-7Nb has been shown to provoke a brief inflammatory response that was similar to that associated with cpTi, but subsequently to lead to highly satisfactory biological outcomes [106,107]. There is also some evidence that Ti-6Al-7Nb promotes better spreading of osteoblast-like cells than cpTi [108] and that its ability to undergo osseointegration in animal models (dogs) is good [109].

Electrochemical studies have been carried out to determine the corrosion behaviour of Ti-6Al-7Nb. In Hank's solution, a composition designed to mimic physiological fluids from the body, Ti-6Al-7Nb showed high corrosion resistance and good stability [110]. Mechanical strength and wear resistance were also found to be good when Ti-6Al-7Nb was prepared as castings [103], which confirmed the promise of this alloy for use as dental prostheses.

Overall, Ti-6Al-7Nb has been shown to have particularly good properties, both physical and biological, for use in dentistry. However, it does not seem to be particularly widely used for this purpose, as far as it is possible to judge from the literature. Most studies concern cpTi, with some considering Ti-6Al-4V, and relatively few explicitly state that they use the alloy Ti-6Al-7Nb. Given the experimental results that implants made from this alloy have shown, this may change in the future.

6. Surface Modification of Titanium Alloys

As has been described already, the surface of the implant is critical for ensuring the necessary osseointegration of dental implants. As well as relying on the natural oxide coating that is found on titanium alloy surfaces, various approaches to altering these surfaces have been studied. These range from roughening, through either acid or alkaline treatment, typically being followed by heating, to coating with an inorganic material such as hydroxyapatite or diamond-like carbon. These approaches will now be considered briefly. As with much of the work on titanium alloys, many of the studies have been aimed at improving materials for orthopaedics, and modifying surfaces specifically for dental implants has been studied much less.

Roughening the surface by some additional processing step has been found to be effective in improving the ability of titanium alloys to undergo osseointegration. This roughening also leads to higher survival rates for dental implants [111,112]. For example, one study compared the survival rates of implants with rough and smooth surfaces, and showed that the survival rates at 20 to 27 months was 98% for the rough surface but only 81% for the smooth one [112]. The roughening process has been shown to alter the surface energy, and this improves the deposition of protein, which in turn enhances the attachment of cells and improves osseointegration of the implant [113].

Surfaces can be roughened by various methods. One involves blasting with particulates, possibly sand, but also alumina, corundum of hydroxyapatite [114]. Another involves etching with

mineral acids such as aqueous HCl and H_2SO_4 of appropriate concentrations [115]. These substances can be used as the only treatment, or can be combined with sandblasting to produce surfaces of differing degrees of roughness [116]. The combined roughening approach has been shown to be especially successful in producing surfaces that develop close early contact with bone following implantation [116], though over the longer term (six weeks or more) there was no advantage in using this technique, and bone contact with the implant surface was no longer improved by it having been done.

Acid-etching to roughen surfaces is not the only chemical method that has been used. Alkaline treatment has also been used to alter surfaces, though this tends not alter surface roughness but to affect surface charge. As an example, it has been found that treatment of titanium alloy with strongly concentrated NaOH solution results in a sodium titanate surface that interacts more actively with bone and more readily promotes growth [117]. Alkaline treatment results in a negatively charged surface that rapidly adsorbs calcium ions from body fluids [118,119]. In vitro studies using simulated body fluid (SBF) have shown that the initial adsorption of Ca^{2+} ions is quickly followed by deposition of phosphate ions and the eventual formation of hydroxyapatite [118,119]. The sequential nature of this deposition process has been confirmed by X-ray photoelectron spectroscopy [116,120]. However, despite this success, such alkaline treatments have mainly been considered for orthopaedic devices [121,122] rather than for dental implants.

One other method that has been widely studied for modifying implant surfaces is anodic oxidation. This is an accelerated electrochemical process that leads to the formation of a substantial oxide coating on the metal surface [123]. The development of such a thick oxide coating on titanium implants may improve corrosion resistance [124], as well as enhancing the bonding of bone cells to the surface [125,126].

A coating formed by anodic oxidation depends on a number of features of the electrochemical process, including anode voltage and the composition of the electrolyte solution. High voltages tend to produce thicker and more porous oxide coatings than lower voltages [127]. Various types of electrolyte solution can be used, such as solutions of sulfuric acid, phosphoric acid or ethanoic acid, as well as neutral salts, or even alkaline solutions, such as aqueous calcium or sodium hydroxide [128,129], and a variety of thicknesses and crystal structures of titanium dioxide have been produced. Despite these successes, it is not clear to what extent such approaches are used on practical implant devices. Indeed, there have been no reports on the long-term effects of these observed improvements in cell attachment and corrosion resistance, and with the present level of knowledge, it is not clear that surfaces prepared in this way offer any clinical advantages over oxide finishes that occur naturally on titanium alloy implants.

The most obvious substance to use to coat implants is hydroxyapatite, and this has been used successfully in orthopaedics to develop so-called cementless prostheses [130]. Hydroxyapatite coating has also been used for dental implants [131] with the aim of improving the rate of osseointegration [132]. The hope is to shorten treatment times, especially for patients whose bone quality is poor [133,134].

Early results with coatings applied to dental implants in the 1990s were not good for various reasons, including detachment of the hydroxyapatite coating and dissolution of the detached HA [131,135]. However, recently coating methods have been improved, and techniques such as ion-sputtering or thermal plasma treatment have been used [136,137]. This has resulted in more durable coatings that adhere better to the titanium substrate and therefore have greater promise for clinical use. This has led to renewed interest in coating dental implants. The demands of specific locations suggest that coated implants might be necessary in order to ensure optimum clinical results. For example, hydroxyapatite screw implants have been recommended for the anterior maxilla and the posterior mandible [138]. However, uncertainty remains about the long-term durability of these coatings remains, and although research is continuing on hydroxyapatite-coated dental prostheses, they are used on only a minority of clinical implants in current practice [139]. The high bioactivity of titanium alloy surfaces, together with the ability to undergo osseointegration reliably means that any improvement from hydroxyapatite

coatings would have to be substantial, and current coatings have not yet shown the necessary levels of improvement.

Another material that has been used to coat dental implants, at least for experimental study, is diamond-like carbon (DLC) [140,141]. This is an amorphous material that has high inherent biocompatibility with bone, and has been applied using chemical vapour deposition onto heated cpTi abutment screws [140]. The application technique can be varied somewhat, and can include electrodeposition [142]. It should ideally include the deposition of an intermediate layer, such as amorphous silicon, to promote adhesion of DLC to the substrate [143]. The aim has been to produce surfaces of improved corrosion resistance and enhanced biocompatibility, and there is experimental evidence that success with these aspects can be achieved in vitro [142,144,145]. However, despite this promise, this approach has not yet had any impact on clinical practice, and DLC-coated dental implants are not yet being used in patients.

7. Conclusions

This paper has described the reasons that titanium alloys are the materials of choice for the fabrication of dental implants. The principal alloys in practical use are commercially pure titanium and Ti-6Al-4V. The mechanical properties of the latter are better, but the slight concern over the biological effects of the very minor amounts of aluminium and vanadium that they release means that cpTi is the more widely used of the two. Despite these concerns, there is a large amount of experimental evidence to show that both alloys have good bioactivity and the ability to osseointegrate. Additionally, there are few, if any, accounts of adverse effects arising from release of aluminium and/or vanadium from dental implants, probably because amounts released are so low.

The result of the excellent biological and mechanical properties of titanium alloys is that success rates with dental implants made of these materials are very high. Various studies are described which show that failure rates over considerable time periods are extremely low. Depending on the details of the study and the materials used, at least 89% and typically 97–99% of implants survive for over 10 years. Given these results, the scope for improving either the materials or the clinical procedures is limited. For this reason, the two well-established alloys of titanium continue to be used for the overwhelming majority of implants used in dentistry, and this use seems likely to continue for the foreseeable future.

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