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Review

The physicochemical/biological properties of porous tantalum and the potential surface modification techniques to improve its clinical application in dental implantology

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ABSTRACT

More rapid restoration and more rigid functionality have been pursued for decades in the field of dental implantology. Under such motivation, porous tantalum has been recently introduced to design a novel type of dental implant. Porous tantalum bears interconnected porous structure with pore size ranging from 300 to 600 μm and a porosity of 75–85%. Its elastic modulus (1.3–10 GPa) more closely approximates that of natural cortical (12–18 GPa) and cancellous bone (0.1–0.5 GPa) in comparison with the most commonly used dental materials, such as titanium and titanium alloy (106–115 GPa). Porous tantalum is highly corrosion-resistant and biocompatible. It can significantly enhance the proliferation and differentiation of primary osteoblasts derived from elderly people than titanium. Porous tantalum can allow bone ingrowth and establish not only osseointegration but also osseoincorporation, which will significantly enhance the secondary stability of implants in bone tissue. In this review, we summarize the physicochemical, mechanical and biological properties of porous tantalum. We further discuss the performance of current tantalum dental implants and present the methodologies of surface modifications in order to improve their biological performance.

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1. Introduction

In recent years, dental implants have become one of the main treatments when replacing the missing teeth. In comparison with other conventional methods (e.g. fixed prosthesis, removable partial denture and removable full denture), the use of dental implants is advantageous in esthetics and comfort as well as the preservation of natural teeth and bone tissues. Hitherto, titanium and its alloys are the most commonly used materials to fabricate dental implants due to their attractive physicochemical, mechanical, and biocompatible properties [1]. A high successful rate has been reported for titanium implants in clinical applications. However, concerns have also been raised for their relatively high modulus of elasticity, low shear strength and frictional characteristics [2], cytotoxicity [3] and potential allergy [4]. In addition, the corrosion products from titanium implants may result in a local and systemic inflammation and even implant failure [5–9]. These limitations of titanium have led to continuous efforts to search for more suitable implant materials.

Tantalum has shown to be a promising material for biomedical applications [10–15]. Tantalum is highly inert and resistant to acid corrosion, thus bearing very good biocompatibility. Although tantalum has already been used in fabricating medical devices since 1940s [16–18], the application of tantalum implants in orthopedics and dentistry was limited by a too high mechanical strength as well as the high costs for purification and fabrication. To overcome these limitations, a novel tantalum material with interconnected porous structure was developed in 1990s. The 3-dimensional geometry of porous tantalum is similar to that of trabecular bone with a porosity of approximately 75%–85% that is much higher than conventional metallic scaffolds. The porous structure can facilitate the ingrowth of bone tissue and form anchorage, thus significantly enhancing the bonding strength between bone and implant [13,14,19,20]. In addition, the elastic modulus of porous tantalum (2.5–3.9 GPa) more closely approximates those of cancellous (0.1–0.5 GPa) and cortical (12–18 GPa) bone than the titanium (106–115 GPa), cobalt chromium (210 GPa), or stainless steel (230 GPa) materials that are used for orthopedic implants [21–23]. Porous tantalum has been applied to fabricate artificial knees [24,25], hip joints [21,23,26], and spinal fusion cages [27–29]. Numerous reports showed high success rates and good treatment effects with porous tantalum medical devices. These excellent properties confer porous tantalum a very promising application potential in the field of dental implantology [30,31]. On the other hand, the highly stable chemical properties of tantalum metal may delay its bonding to bone tissue and bone ingrowth into porous structures, which might account for implant loosening [31,32]. Consequently, further surface modification is needed to improve the bioactivity and efficacy of porous tantalum. This is also important to meet the increasing demand for earlier loading and functionality of dental implants.

In this study, we will summarize physicochemical, mechanical and biological properties of tantalum and porous tantalum. In order to facilitate its application in the field of dental implantology, we will then summarize the performance of current tantalum dental implants and present the potential methodologies of surface modifications in order to improve their biological performance.

2. Physicochemical, mechanical and biological properties of tantalum

Tantalum element was discovered by a Swedish chemist and mineralogist, Anders Gustaf Ekeberg [33] in 1802. In 1903, Werner bon Bolton for the first time refined and obtained a sample of relatively pure tantalum metal [33]. Tantalum is a chemical element with the symbol Ta and atomic number 73. Tantalum is a rare, hard, blue-gray, lustrous transition metal with high corrosion resistance [34,35]. It belongs to the refractory metal group, which includes titanium, hafnium, niobium and rhenium [15]. Tantalum has an extremely high melting point of 3017 °C, which is exceeded only by some metals, such as rhenium, osmium or tungsten [15]. It is also highly conductive to heat and electricity. Pure tantalum metal is relatively active in chemical properties. It has a higher affinity for oxygen, nitrogen, carbon and hydrogen than other refractory metal elements. Tantalum can be easily oxidized to different oxide states, $+5$ (Ta_2O_5) and $+4$ (TaO_2). The most stable one is the $+5$ (Ta_2O_5). When exposed in air, a passivation layer of Ta_2O_5 is formed on the surface of tantalum, which accounts for its unparalleled corrosion resistance. At a temperature below 150 °C, tantalum resists chemical attack from almost all strong acids including hydrochloric acid or nitric acid. Only hydrofluoric acid, fuming sulfuric acid and potassium hydroxide (KOH) can etch the tantalum metal [36].

Tantalum has been proven to be highly biocompatible in various forms of medical devices, such as rods [37–39], wires [15,40], artificial joints [41–44], spinal fusion cages [27],dental implants [31], micro- or nano-particles [35,45], and radio markers [46,47] both in vitro and in vivo. No evidence is shown to indicate cytotoxicity of tantalum to the cultured osteogenic cells and mesenchymal stem cells [48–50]. The biocompatibility of tantalum is higher in bulk form and significantly higher in powder than titanium [3]. In different animal models, tantalum demonstrates no remarkable inflammatory response, regardless of the implantation positions, types of tissues and the forms of implants [15,51].

3. “Trabecular metal” — porous tantalum

The biomedical application of solid tantalum metal was ever limited due to its high mechanical strength and density (16.68 g/cm^3) that are too rigid for bone tissue [52] and high costs in purification and fabrication [53]. To overcome these limitations, porous tantalum scaffolds have been developed in 1990s to optimize the mechanical properties. This porous tantalum bears an interconnected porous structure, which is similar to human cancellous bone (Fig. 1). Average diameter of the pores ranges from 350 to 450 μm with a porosity from 75% to 85% [54], which is much higher than other porous metallic materials. The micrographs of scanning electron microscopy (SEM) show that the struts with average length of 465 μm are joined together at intersection nodes to surround the pores in a shape of dodecahedron [55]. Using different fabrication methods, various topical microtextures can be formed on the struts, which are friendly to cell attachment [55]. Porous tantalum is comprised of approximately 99% tantalum and 1% impurities by weight [54].

3.1. Fabrication methods of porous tantalum

Until now, two main methods have been developed to produce porous tantalum: chemical vapor infiltration and deposition (CVI/CVP) [56] and powder metallurgy (PM) technique [52]. In the CVI/CVP method, tantalum is chemically vaporized, infiltrated, and deposited on the surface of a low-density vitreous carbon skeleton with a porosity of 98% to produce a tantalum layer. The thereby produced porous tantalum bears a pore size of 400–600 μm and a porosity of 75–80% [57]. Since the shape and mechanical characteristics of the final tantalum scaffolds are mainly determined by the geometry of initial carbon skeleton and the thickness of tantalum layer, the CVI/CVP method enables the production of porous tantalum with nearly limitless properties to meet various requirements [57]. The PM technique impregnates polyurethane sponge blocks into tantalum slurry. After drying in vacuum, the specimen is heated in the vacuum furnace at 1950 °C for 2 h with the heating/cooling rate of 10 °C/min. The thereby produced porous tantalum shows a structure with a pore size of 300–600 μm and a porosity of about 66.7% [52]. Recently, Zhou and Zhu reported a novel fabrication method of tantalum foam by replications of sodium chloride particles as space-holders [58]. Briefly, tantalum particles and sodium chloride particles are mixed homogeneously and heated at 1800 °C for 90 min under protection from argon gas. After thermal treatment, the samples