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OPTIMAL FEATURES OF POROSITY OF Ti ALLOYS CONSIDERING THEIR BIOACTIVITY AND MECHANICAL PROPERTIES

ABSTRACT

This article reviews the influence of porosity and pore sizes of titanium and titanium alloys, used as orthopaedic materials, on bioactivity and mechanical properties of the porous structures. The optimal features of porous titanium scaffolds allow the reconstruction and regeneration of bone tissue in load-bearing applications.

Key words: *bioactivity, mechanical properties, porosity, pore size, titanium*

INTRODUCTION

Among various metallic biomaterials, titanium and its alloys are widely used in biomedical field for hard tissue replacements because of their desirable properties, such as relatively low elastic modulus, good fatigue strength, formability, and corrosion resistance [1,2]. However, most titanium implants are still not sufficient for long-term clinical usage because relatively high stiffness of titanium, as compared to surrounding bone, can cause stress shielding leading to subsequent implant loosening. Also, the biocompatibility and bioactivity of these materials must be improved in order to reduce time for osseointegration and increase implant life-time. To overcome these problems the porous titanium structures can be considered [3]. They is an advantageous alternative because the elastic modulus can be adjusted to match that of bone, preventing bone resorption and implant loosening. Furthermore, porous titanium implants provide three-dimensionally interconnected pores which permit the transportation of body fluids, vascularisation and in-growth of bone tissue [4,5].
Porous titanium structures are fabricated using various fabrication methods, including gas injection into metal melt [6], compressing and sintering of titanium fibers [7,8], solid-state foaming by expansion of argon-filled pores [1,3,9], polymeric sponge replication [10], spark plasma sintering (SPS) [11], field assisted consolidation technique (FAST) [12], solid freeform fabrication [13], self-propagating high temperature synthesis [14], powder metallurgy [1] and rapid prototyping technology, like three-dimensional fiber deposition (3DFD) [15-17].
None of the conventional techniques (plasma spraying, sintering, compression, solid state-foaming or polymeric sponge replication) does not allow to prepare titanium

scaffold with precisely defined external shape as well as the internal interconnected pore network. In contrast, by using rapid prototyping method, Lopez-Hereida *et al.* [15] have produced a porous Ti implant with well defined structure and a specific shape and pore size. Many other researchers have proved that this method is very suitable for preparation of customized, very well controlled and defined, porous structures [15,16,18].
Additionally, the bioactivity of the porous Ti scaffolds can be improved significantly by coating their inner and outer surfaces with bioactive materials as hydroxyapatite, widely discussed in [19].

POROSITY AND PORE SIZE

An ideal structure of bone scaffold should have a sufficient porosity with adequate pore size and pore interconnectivity to promote cellular functions in order to mimic natural extracellular matrix of bone tissue. A porous network will promote vascularisation for bone ingrowth, rapid bone regeneration and good implant integration. Also, the pore interconnectivity is necessary to enable access of blood and nutrients for bone mineralization [20]. An optimal pore size range is considered to be 100 ÷ 500 μm with open porosity up to 40 ÷ 80 %; however, there is no consensus on this matter [20-24]. In fact, exact pore sizes and porosity cannot be suggested as a general rule due to the wide range of bone features itself. Bone, on macrolevel can be classified into spongy bone with many different pores and porosity, and lamellar bone with compact cylindrical osteons [25]. In research performed by J-P. St-Pierre *et al.* [23] it has been proven that the pore size has got an significant effect on the proliferation stage of cells, while differentiation and subsequent mineralisation processes are rather unaffected. Increased porosity and pore size facilitate more bone ingrowth into the scaffold. It also should be kept in mind that although relatively high porosity and increased pore size are obviously preferential for new bone ingrowth into porous titanium implants, it can results in reduction of the scaffold's mechanical properties which are very important for the load-bearing applications. Using different fabrication method of titanium scaffolds, the variety of results has been achieved as shown in Table 1, considering their porosity and pore size range.

Table 1. *Porosity and pore size of porous titanium and titanium alloy implants*

Material of implant	Porosity [%]	Pore size [μm]	Fabrication method	Reference
Ti	50	1000	Rapid prototyping	[15]
Ti	67	150 ÷ 600	Fiber sintering	[26]
Ti	85	200 ÷ 300	Fiber sintering	[27]
Ti	40 ÷ 60	300 ÷ 500	Fiber sintering	[28]
Ti	65 ÷ 70	350 ÷ 550	Powder metallurgy (space-holder method)	[29]
Ti	60	125 ÷ 250; 355 ÷ 500	Powder metallurgy	[24]
Ti	~ 40	100 ÷ 300	Sintering titanium beads	[30]
Ti	75	100 ÷ 500	Polymeric sponge replication	[24]

Ti	14 ÷ 44	300 ÷ 500	Solid-state foaming technique	[31]
Ti	53 ÷ 55	200 ÷ 400	Powder metallurgy (space-holder: urea powder)	[32]
Ti	~ 45	~ 465	Rapid prototyping	[33]
Ti	78	500 ÷ 800	Polymer impregnating method	[34]
Ti	60	50 ÷ 200	Powder metallurgy (gas forming agent: TiH_2)	[1]
Ti	80	200 ÷ 500	Powder metallurgy (space-holder: ammonium biocarbonate)	[35]
Ti	72	500 ÷ 1000	Slurry method	[36]
Ti	45 ÷ 70	~ 525	Powder metallurgy (space-holder: magnesium)	[37]
Ti	30	300 ÷ 560	Powder metallurgy	[23]
Ti6Al4V	60 ÷ 75	~ 400	Powder metallurgy (space-holder: carbamide)	[38]
Ti6Al4V	49 ÷ 74	400	Rapid prototyping: Three-dimensional fiber deposition (3DFD)	[16]
Ti6Al4V	39 - 68	160 ÷ 680	Rapid prototyping: Three-dimensional fiber deposition (3DFD)	[5]
Ti18Nb4Sn	~40	50 ÷ 450	Powder metallurgy	[39]

BIOACTIVITY OF POROUS TITANIUM SCAFFOLDS

There is an interface problem, as the titanium material has the bioinert character, which means that its natural protective surface oxide does not readily form a strong interface with surrounding tissue. There are some methods applied to resolve this problems, like coating titanium surface with hydroxyapatite using plasma spraying [40], sol-gel [41,42], electrodeposition [15], electrophoretic deposition [43], biomimetic deposition [1], solution phase apatite growth [44]. There are some drawbacks in using above methods, such as difficulties in deposition of CaP coatings inside porous structure (inner surface) and weak bond strength on the interface coating/metallic substrate [45].

Bioactive porous titanium implants act as a scaffold for cells, enabling them to anchor, attach and proliferate [46]. As noticed during the experiments conducted by Spoerke *et al.* [3] the cells tend to bridge all pores smaller than 75 μm and easily grow into pores larger than 200 μm.

The initial contact between the cells and the substrate is largely determined by the distribution and adhesion proteins adsorbed onto the substrate of the metallic biomaterials [47]. Cells are sensitive to the proteins and use them as anchoring points which enable them to attach to the substrate through extending filopodia, which in turn are preferentially attached at micropores on the surface of metallic scaffolds.

Apatite forming ability

To improve the biological properties and enhance the bioactivity of the titanium scaffolds (promoting bone ingrowth into its porous structure and establishing a strong implant/bone interface at early postimplantation period), surface modifications or coating with calcium phosphate bioactive material can be used [48]. There are some methods for coating of porous titanium, like plasma spraying [49], biomimetic deposition [50], sol-gel method [51], electrophoretic deposition [52]. Among the surface modification methods, the most appropriate are: alkali and thermal treatment [45], and micro-arc oxidation (MAO) [48].
To improve the biological properties of the titanium scaffolds, apatite coatings can be applied onto the surface of Ti alloy, by chemical treatment and by immersing in a simulated body fluids [1]. Chemically treated surface of porous titanium and titanium alloy have the ability to induce the bone-like apatite nucleation and growth form SBF [1].
The in vivo bioactivity of the biomaterial can be precisely mirrored by its apatite-forming ability in a simulated body fluid (SBF), where the ions concentration is nearly equal to those of human blood plasma [48,53]. Chen et al. [35] evaluated the apatite-inducing ability of the porous and nonporous samples of porous titanium in m-SBF, which has a longer stability than the standard SBF [54-56]. They have demonstrated that no apatite is deposited on untreated Ti but the alkali-heat treated sample have the best apatite-inducing ability, which is connected with the surface energy.

EFFECTS OF POROSITY ON MECHANICAL PROPERTIES

The mechanical properties and biological functions of titanium scaffolds are strongly influenced by their pore structures, such as porosity, pore size, pore orientation and interconnections between the pores [57]. A proper design of porous titanium implants must balance the biological need of high open porosity for maximum bone ingrowth with the mechanical demands of material integrity for long-term implant performance in load-bearing applications. The porous titanium implants should match their mechanical properties, particularly elastic modulus and stiffness, to those of the surrounding bone and provide a favourable environment for bone ingrowth. It has been reported that the elastic modulus of titanium scaffold could be adjusted to match with that of a natural bone for eliminating the stress shielding by altering its porosity [58-60] as listed in Table 2. Although increased porosity and pore size facilitate bone ingrowth, the result is a reduction in mechanical properties, so the compromise in mechanical properties with increasing porosity should set up an upper limit to maximum porosity and pore size of the porous titanium implant.

Table 2. *Elastic modulus of titanium scaffold as a function of materials porosity*

Material of implant	Porosity [%]	Pore size [μm]	Elastic modulus [GPa]	Reference
Ti6Al4V	43 59	-	9.5 5.8	[1]
Ti	50	1000	2.7 ÷ 9.8	[15]
Ti	78	200 ÷ 500	5.3	[35]
Ti	22	70 ÷ 200	40 ÷ 20	[3]
Cancellous bone	*30 ÷ 95*	*20 ÷ 1000*	*2.3 ÷ 20*	[61]

The porosity of 40 – 50% is considered as an optimal range to provide reduced stiffness to titanium scaffolds and adequate site for bone ingrowth while maintaining mechanical durability for long-term usage of the implant [21]. Other researchers have proposed the value of porosity at least 60 % [22]. Although, pores dispersed throughout titanium matrix cause stress and strain concentrations resulting in reduced mechanical properties, bone infiltration is a key factor to improve them by delaying plastic deformation of the porous titanium implant and alleviating stress concentrations in porous microstructure under the physiological loading, as proved by using finite element modelling method (FEM) conducted by Shen *et al.* [31]. Similar results have been obtained by other researchers based on developed FEM models of metallic scaffolds predicting the stress and strain concentrations of porous titanium implant with respect to the complex loading conditions in scaffold under the physiological loading [3,37,62]. Naturally, all the theoretical FEM models are based on the idealized microstructures, e.g. uniform spherical, cylindrical or cubic pores arranged in a regular arrays, and therefore the derived correlations between properties and porosity are approximate comparing to real materials with pores of irregular shapes, non-uniform size and random distribution.

CONCLUSIONS

Nowadays, owing to increasing life expectancy and long-term failure of orthopaedic implants, there is a shift from simple bone replacement to bone regeneration by stimulating the body's natural regenerative mechanism.
The success of an orthopaedic implant is determined by the intimate interaction between the implant and the host tissue at the implant/tissue interface. The fabrication of the scaffolds with gradients in porosity and pore sizes that will allow on one side the high vascularisation and direct osteogenesis, while promoting osteochondral ossification on the other, having the optimal mechanical properties, can mimic the complex architecture of bone-specific sites and optimize bone tissue regeneration.

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