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Characterization of the structure and permeability of titanium foams for spinal fusion devices

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Abstract

Titanium foams produced via the space-holder method are used for spinal fusion devices since their combination of an open-cell structure and bone-like mechanical properties promises potentially excellent bone ingrowth. Earlier studies have indicated that the size of the pores and interconnects must be greater than 100 μm for effective bone ingrowth and vascularization. Hence, the quantification of the pore and interconnect size is required for efficient scaffold design. In this study, microcomputed tomography (μCT) was used to obtain the three-dimensional (3D) structure of Ti foams with three levels of porosity (51%, 65% and 78%). Novel algorithms were then applied to quantify both the pore and interconnect size of Ti foams as a function of porosity. All foams possessed a modal pore and interconnect size in excess of 300 μm, satisfying the requirement of being greater than 100 μm. The pore and interconnect size also dominates the flow properties or permeability of open-cell structures. Therefore, the μCT data was also used to generate a mesh for computational fluid dynamics analysis to predict the permeability. The calculated permeability (117–163 $\times 10^{-12}$ m^2 depending on direction) for the Ti foams with 65% porosity was first validated against experimental measurements (98–163 $\times 10^{-12}$ m^2) and then compared to prior authors' measurements in healthy cancellous bovine bone (233–465 $\times 10^{-12}$ m^2). The close match among all the permeability values proves the suitability of the material for biomedical skeletal-implant applications.

Keywords: Titanium foams; Tissue scaffold; Porosity; Permeability; Microcomputed tomography

1. Introduction

Commercially pure titanium foam is one of the accepted materials of choice for implant applications since it has excellent mechanical, corrosion resistance and biological (biocompatibility and osteoconductivity) properties [1–7]. However, implants made from monolithic Ti alloys with polymer and/or ceramic coatings have illustrated limited lifetimes due to interfacial instability with host tissues, mechanical mismatch of the elastic moduli, production of wear debris and inadequate blood supply [8]. Recently, there have also been many studies investigating the use of ceramic (e.g. hydroxyapatite or bioactive glass) and polymer materials to form open-cell porous materials, termed scaffolds, into which bone ingrowth and vascularization can occur. However, these materials have a lower strength and/or ductility than is desired [9] and some can resorb more rapidly than bone ingrowth occurs [10]. There is therefore an ongoing search for a material with structure and properties similar to trabecular (cancellous) bone to be used as a scaffold upon which to grow bone either in vitro or in vivo [11,12].

Another benefit of metallic foams is that the Young's modulus can be fine tuned to match the modulus of the bone in order to avoid stress-shielding effects which can

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lead to a high rate of bone resorption. The mechanical behaviour of a porous scaffold is dependent on the pore volume fraction and size distribution as this determines the size of the struts or walls between the pores which are bearing the load. Depending on the process used in making the foam, its micro/macrostructure can be tailored to optimize the "biofactor" (cell, gene and/or protein) delivery and mechanical properties by incorporating well-connected pores [13].

Fujibayashi [14] recently reported that open-cell structures made from titanium illustrated good osteoinductive behaviour at a non-osseous site achieved through a special chemical and thermal treatment. Scaffolds made from titanium might therefore be a promising system for bone implants. The study of Fujibayashi et al. was a demonstration of the feasibility, but they did not quantify the structure in terms of pore and interconnect size. It is accepted that the minimum pore size for in vivo bone ingrowth into a material is about 100 μm; therefore the foams produced should have interconnects of at least 100 μm in diameter between their macropores [15–17]. There is therefore a strong need for effective methods to quantify the size distribution of pores and interconnects.

The size of these interconnects can also affect the flow properties, which are important for cell seeding and nutrient delivery for in vitro bone growth, as well as in vivo for subsequent ingrowth and vascularization [18–20]. Permeability is one measurement by which the flow properties crucial to the in vivo performance of a scaffold as a bone implant may be measured. Permeability depends upon the scaffold's internal topology. If the topology can be quantified, the Navier–Stokes equations can be used to solve for the permeability computationally, including any anisotropy [21]. It is also possible to calculate the permeability analytically as a function of the scaffold's porosity, surface or interconnect size depending on the simplifying assumptions made [22].

Despite recognizing that pore and interconnect size and morphology will be critical in influencing biological and mechanical performance of a tissue-engineered scaffold, their precise three-dimensional (3D) quantification and characterization [23–25] have received only limited attention. In an evaluation of the biological performance of scaffolds, conventional techniques based on 2D image analysis and mercury intrusion porosimetry can be insufficient in estimating permeability and pore size. Shen et al. [26] performed 2D image analysis on Ti foams and then mapped the results into 3D models for the purpose of simulating foaming and mechanical properties. Although they performed a 3D tomographic scan of an experimental foam, they compare the results only qualitatively rather than quantitatively. Recently, Otsuki et al. [25] presented the most detailed analysis of a Ti foam to date, using image analysis of microcomputed tomography (μCT) data to calculate the path length from pores on the interior to the outer surfaces, based on percolation theories developed for analysing rock samples [27]. Using iterative dilation, they then ranked the pores by the minimum interconnect size along the connecting path. However, the individual quantification of pore and interconnect size and morphology was not determined, hence their distributions cannot be plotted. Although it has not been applied to Ti foams, one of the authors and co-workers developed an algorithm that detects individual pores and interconnects and have applied it successfully to bioactive glass foams [23]. This technique uses a watershed algorithm [28] and a custom distance map to first isolate and label individual pores, followed by the subsequent identification of the areas connecting them. In the field of porous rock characterization, Lindquist et al. [29] developed a technique based on medial surface/axis thinning algorithms [30] to perform similar characterization of individual pores in open-cell structures.

In this paper, a state-of-the-art μCT unit was used to characterize the structure of porous titanium scaffolds at three porosity levels, namely 51%, 65% and 78%. Image analysis techniques [23] were then applied to analyse size distributions of porosity and interconnects. A new methodology for comparing the size distributions of interconnects in different materials is presented. The permeability of titanium fusion implant scaffolds are derived via simulations from the μCT data for the first time, and validated against experimental measurements as well as analytic approximations. The characterization of both the structure and permeability is then compared to the properties of bone and those required for an ideal scaffold.

2. Materials and methods

2.1. Titanium foam preparation

Open-cell titanium foams were produced using powder metallurgy combined with the space-holder method [6,31,32]. The titanium powder used was Grade 4 commercially pure (CP) titanium having a log-normal particle size distribution with an average d50-value of 25–40 μm. Ammonium hydrogen carbonate ($(NH_4)HCO_3$) was used as the space-holder material, sieved to obtain the desired particle size distribution (425 and 710 μm sieves).

The titanium powder was then mixed with the space-holder substance and subsequently cold-isostatic pressed at 300 MPa into blocks measuring approximately $70 \times 45 \times 50$ mm. This green compact was then held at 95 °C for 12 h in a convection oven to allow complete gaseous decomposition of the ammonium hydrogen carbonate. The foams were then sintered at 1300 °C for 3 h under an argon atmosphere [33].

Differing amounts of space-holder substance were used to obtain three different porosity levels, namely 51%, 65% and 78% (designated as samples P51, P65 and P78, respectively).

2.2. Scanning electron microscopy (SEM)

Samples of each type of foam were examined by SEM (using a 5610LV, JEOL scanning electron microscope) in