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Research Article

Bone Ingrowth into Pores of Lotus Stem-Type Bioactive Titanium Implants Fabricated Using Rapid Prototyping Technique

A. Fukuda,[1] M. Takemoto,[1] K. Tanaka,[1] S. Fujibayashi,[1] D. K. Pattanayak,[2] T. Matsushita,[2] K. Sasaki,[3] N. Nishida,[3] T. Kokubo,[2] and T. Nakamura[1]

[1]Department of Orthopaedic Surgery, Graduate School of Medicine, Kyoto University, Shogoin, Kawahara-cho 54, Sakyo-ku, Kyoto 606-8507, Japan
[2]Department of Biomedical Sciences, College of Life and Health Sciences, Chubu University, 1200 Matsumoto-cho, Kasugai, Aichi 487-8501, Japan
[3]Sagawa Printing Co., 5-3 Inui, Morimoto-cho, Muko, Kyoto 617-8588, Japan
Address correspondence to A. Fukuda, akinobu@kuhp.kyoto-u.ac.jp

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Abstract In the present study, to evaluate the effect of pore size on bone ingrowth, we fabricated lotus stem-type titanium implants each with 4 square holes (diagonal length: 500, 600, 900 and 1200 μm) by using the rapid prototyping process with selective laser melting. These were then subjected to chemical and heat treatments to induce bioactivity. There were significant differences between bone ingrowth on the bioactive-treated and untreated implants. There were no significant differences for bone ingrowth among all holes in both implants. However, in both implants, the 1200-μm was found to be the best for bone invasion in the early stages of growth. On the other hand, both 500- and 600-μm were found to be suitable for bone ingrowth from 6 weeks to 26 weeks in treated implants. Thus, the simple architecture of the implants allowed effective investigation of the influence of the interconnective pore size on osteoconduction.

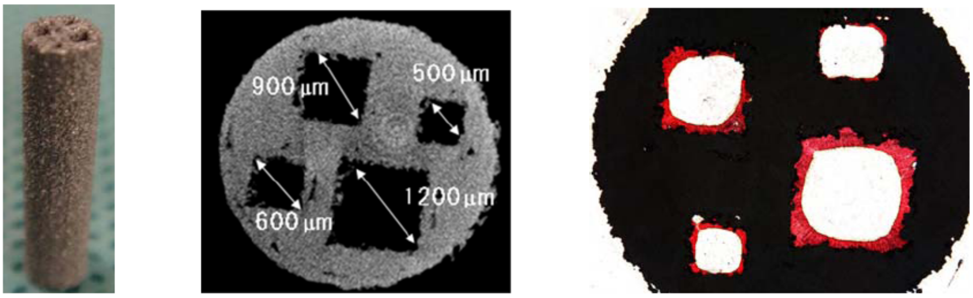
Keywords rapid prototyping; lotus stem-type titanium; osteoconduction; A-HCl-H treatment; selective laser melting

1 Introduction

Titanium metal is frequently used for orthopedic implants because of its superior corrosion resistance, mechanical property, and good biocompatibility. As for the research of biomaterials, its nonresorbable characteristic can be used for the evaluation of appropriate pore size for bone ingrowth. We have developed various types of porous titanium implants using plasma spraying [6] and powder sintering processes. These porous titanium implants show both superior osteoconductivity and osteoinductivity when they are subjected to alkali and heat treatment [1,7]. Recently, we have adopted the rapid prototyping (RP) [2] process with selective laser melting (SLM) [4] to reproduce the designed microstructure of porous titanium implants. There are several important factors to be considered while designing an optimal porous structure, such as porosity, pore size, and interconnectivity [3,5]. In this study, to evaluate the effect of pore-throat size on bone ingrowth, we developed lotus stem-type titanium implants by SLM and investigated their osteoconduction with a change in the pore-throat size.

2 Materials and methods

Lotus stem-type titanium cylinders (diameter: 3.3 mm, length: 15 mm) each with 4 square holes (diagonal length: 500, 600, 900 and 1200 μm) were designed using a computer assisted design (CAD) program and fabricated by SLM (Figure 1). SLM is a layered manufacturing technology involving the use of metal powder. The titanium porous structures prepared from titanium powder (with particle size below 45 μm) were melted using a scanning laser beam. Titanium implants were manufactured by Sagawa Printing Co. according to an instruction of our institution (Figure 2). For bioactive treatment, the implants were soaked in 5 M NaOH aqueous solution at 60 °C for 24 h and then in 0.5 mm HCl (pH 3.4) at 40 °C for 3 h. Then, they were gently washed with distilled water and heat treated in air at 600 °C for 1 h (A-HCl-H treatment) [7]. The effect of surface treatment on the material was evaluated by using a scanning electron microscope (SEM). The animal study, using beagle dogs, was approved by the Animal Research Committee, Graduate School of Medicine, Kyoto University, Japan. For in vivo analysis, 3 samples were implanted into the marrow cavity of the femur and tibia of mature beagle dogs (weight: 10–11 kg). Bioactive-treated implants and untreated implants were inserted in the right and left legs, respectively. Six dogs were used in this study, and they were sacrificed in pairs 6, 12, and 26 weeks after



(a) (b) (c)

Figure 1: (a) Lotus stem-type titanium cylinder (diameter: 3.3 mm, length: 15 mm), (b) cross-section of lotus stem-type titanium cylinder showing 4 square holes (diagonal length: 500, 600, 900 and 1200 μm), obtained by micro-computed tomography (μCT) scanning and (c) nondecalcified histological section of implant after implantation in the legs of mature beagle dogs for 26 weeks, obtained by light microscopy. Stain: Van Gieson's picro-fuchsin.

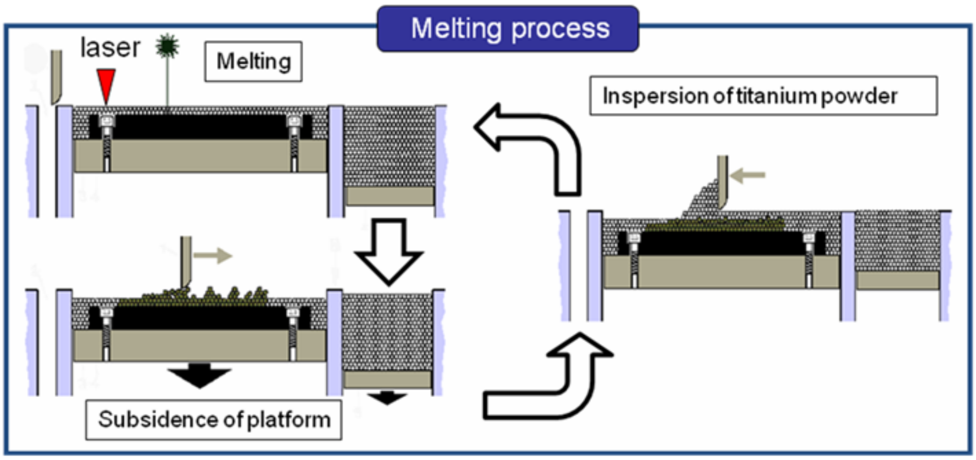


Figure 2: Preparation of laminate molding by repeated melting, subsidence of platform, and inspersion of titanium powder, using slice data generated from 3D-CAD data.

implantation, respectively. For histological analysis, each sample was embedded in a resin and sectioned at every 1 mm. Bone ingrowth into each pore was evaluated by light microscopy and fluorescence microscopy, which revealed that the bone ingrowth distance was 15 mm (Figure 1).

3 Result and discussion

The microporous structure of the lotus stem-type bioactive titanium surface was observed, even on the surface of the 500-μm holes in the section of the center of the cylinders, by using the SEM (Figure 3).

In the animal experiment, there were significant statistical differences ($P < .05$) in bone ingrowth distance in the case of the bioactive-treated and untreated implants. It was found that the lotus stem-type titanium implants subjected to A-HCl-H treatment had excellent osteoconductivity. There were no significant statistical differences in the bone ingrowth distance inside the 4 holes of different diagonal lengths, in both bioactive-treated and untreated implants. However, the 1200-μm holes was found to be the best for bone invasion in the early stages of bone growth, but the bone ingrowth rate gradually decreased with time; on the other hand, both 500 and 600-μm holes were found to be suitable bone ingrowth from 6 weeks to 26 weeks. Similar tendency was also observed in the untreated implants, although the overall bone ingrowth in this case was lower that in the bioactive-treated implants (Figure 4). From these results, we assume that the 1200-μm holes might be too large for bone growth, although they might be suitable for tissue invasion. On the other hand, 500–600 μm holes might be adequate for bone growth, but too narrow for tissue invasion at depths below 3 mm.

4 Conclusions

Lotus stem-type titanium implants were successfully fabricated and subjected to alkali and heat treatment by using the RP process with SLM. These implants were useful for evaluating the effect of pore size and bioactive treatment on

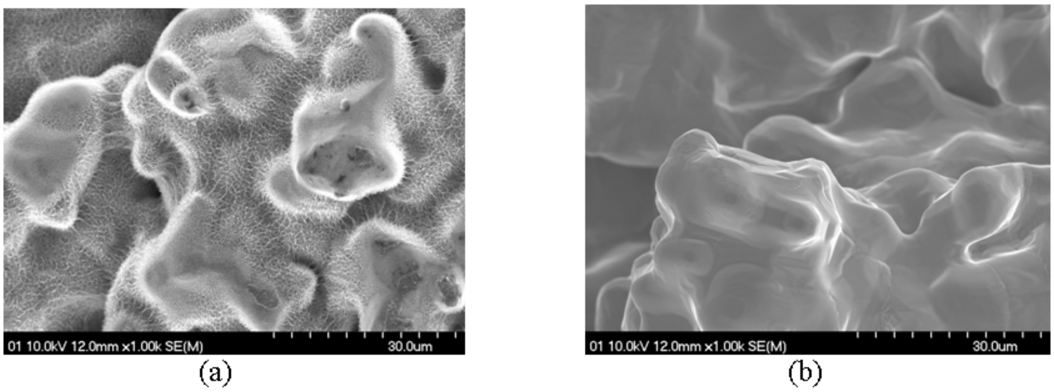


Figure 3: SEM images of the inner surface of 500-μm hole in a section of the center of cylinder: (a) A-HCl-H treated implant, magnification: 1000$\times$ and (b) untreated implant, magnification: 1000$\times$.

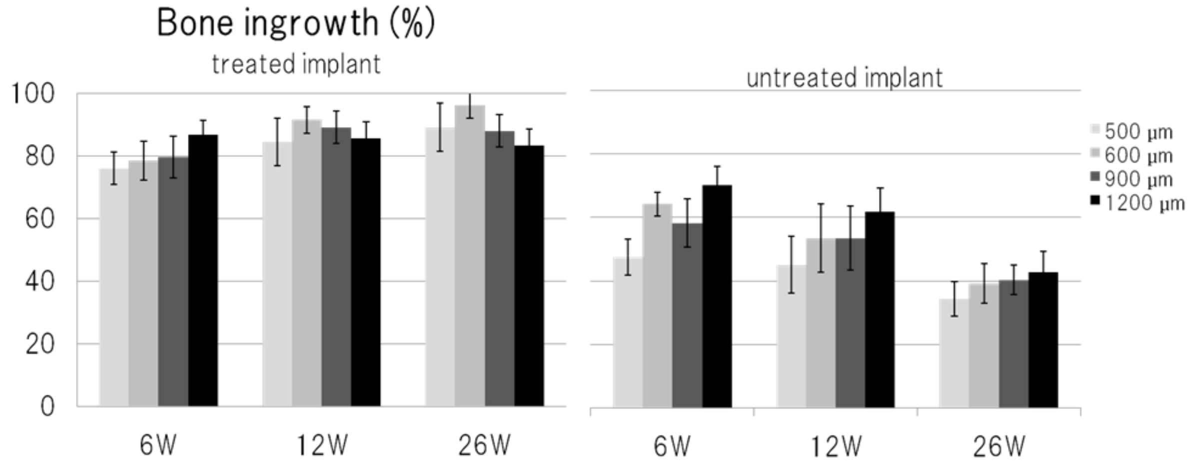


Figure 4: Results of bone ingrowth rate in bioactive-treated implant and untreated implant. Bone ingrowth rate in the former is significantly higher than that in the latter at each period ($P < .05$). The bone ingrowth rate in 1200-μm holes gradually decreased from 6 weeks to 26 weeks in both implants.

bone ingrowth. The results of this study will provide useful information for designing titanium implants with an optimal porous structure by using the RP technique.

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