

## Porous $\beta$ -Tricalcium Phosphate Ceramics of Bimodal Pore Size Distribution

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The difference in microstructure has a large effect on the reaction of the ceramics in the bone. Therefore micro-pores, as well as macro-pores, must be controlled for porous material design, although the size of micro-pores is too small for cells. In this study, porous ceramics of  $\beta$ -tricalcium phosphate ( $\beta$ - $\text{Ca}_3(\text{PO}_4)_2$ ;  $\beta$ -TCP) with bimodal pore size were prepared from porous hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ; HA) with calcium deficient composition synthesized by hydrothermal method. The particle size, shape, and the micro-pore size of about 0.1  $\mu\text{m}$  and macro-pore size of about 100  $\mu\text{m}$  of ceramics were controlled by our unique method. These porous ceramics must be suitable for the bone graft material and the scaffold of cultured bone.

Key words:  $\beta$ -TCP, porous ceramics, biomaterial, hydrothermal

### 1. INTRODUCTION

Hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ; HA) and  $\beta$ -tricalcium phosphate ( $\beta$ - $\text{Ca}_3(\text{PO}_4)_2$ ;  $\beta$ -TCP) porous ceramics with macro-pores over 100  $\mu\text{m}$  in size are currently used as bone graft substitutes [1-5], because macro-pores allow cells to enter easily into the materials. These porous materials have been known to be biocompatible and osteoconductive [6]. Several previous studies have also confirmed that HA is a stable material *in vivo* [7-9] and  $\beta$ -TCP is more biodegradable as the implant material than HA [10-12]. In addition, the authors reported that micro-pores of  $\beta$ -TCP with about 0.1-0.5  $\mu\text{m}$  in size were significantly important for bio-resorption in bones [13], therefore both macro-pores and micro-pores should be controlled for porous ceramics of  $\beta$ -TCP.

The present paper deals with the hydrothermal preparation of porous HA and  $\beta$ -TCP with designed bimodal pore structure.

### 2. EXPERIMENTAL PROCEDURE

#### 2.1 Preparation

Commercial powders of  $\alpha$ -tricalcium phosphate ( $\alpha$ - $\text{Ca}_3(\text{PO}_4)_2$ ;  $\alpha$ -TCP, Taihei Chemical Industrial Co., Ltd., Japan) were used as the starting material. After the addition of 50-75 mass%

glycine particles of about 100-200  $\mu\text{m}$  in size ( $\text{H}_2\text{NCH}_2\text{COOH}$ , Wako Chemical Co., Japan) to  $\alpha$ -TCP, the mixed powders were formed into cylindrical shape of 8 mm $\phi$   $\times$  10 mmL with about 60 % porosity. The samples were set in a 105 cm<sup>3</sup> autoclave with 10 cm<sup>3</sup> of dilute aqueous ammonia addition, then they were exposed to vapor of the solution at the temperatures from 30<sup>o</sup> to 240  $^{\circ}\text{C}$  under the saturated vapor pressure for 20 h. Then the samples were heated at 900  $^{\circ}\text{C}$  for 3 h in air for preparation of  $\beta$ -TCP.

#### 2.2 Characterization

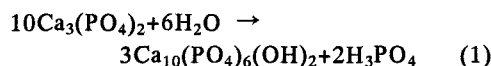
The produced phases were identified by powder X-ray diffractometry with Ni filtered  $\text{CuK}\alpha$  radiation, operating at 40kV and 20mA (XRD; Mac Science, MXP<sup>3</sup>, Japan). The HA content in the prepared samples was estimated by XRD precise measurement. The relative intensity of XRD lines for HA and it for  $\beta$ -TCP was used in order to determine the HA content [14]. The samples prepared were dissolved in nitric acid of 0.1 mol  $\cdot$  dm<sup>-3</sup>, and then the chemical composition of them was analyzed by inductively coupled plasma spectrometer (ICP-MS; Seiko Instruments, SPQ 9000S, Japan). The microstructure of specimens was observed by scanning electron microscope for the surface and for the fractured surface (SEM; JEOL, JSM-25S, Japan). Pore volume and distribution of pore diameter were

measured by mercury intrusion porosimetry (MIP; Carlo Elba, Porosimeter 2000, Italy). The compressive strength of porous materials was measured by mechanical testing machine (Tokyo Testing Machine, UTM Type RAT30, Japan).

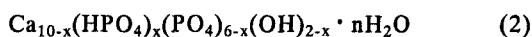
### 3. RESULTS AND DISCUSSION

#### 3.1 Porous ceramics of hydroxyapatite

Cylindrical samples exposed to vapor of aqueous ammonia were hardened because of formation of HA as the bonding material from  $\alpha$ -TCP [15]. In the present experiment, HA was formed at the temperatures above 40 °C, and then no phases other than HA were revealed by XRD for the samples treated at the temperatures above 105 °C. The reaction between  $\alpha$ -TCP and water was considered as follows (Formula (1)), if the obtained HA was the stoichiometric HA.



Indeed, the treating solution after hydrothermal treatment was dilute aqueous solution of phosphoric acid according to ICP-MS analysis. The value of pH of the treating solution was about 4.5. However, the produced HA was not stoichiometric HA, that was calcium deficient HA. In general, chemical formula of calcium deficient HA is described as follows.



The authors reported that composition of this apatite could be controlled [16]. The Ca/P ratio of the samples increased from 1.50 to 1.63 with increasing treatment temperature [16], but the Ca/P ratio of the samples was lower than that of stoichiometric HA (stoichiometric Ca/P=1.67).

Porosity of the samples increased with increasing additional amount of glycine. This porous HA ceramics had the porosity from about 70 % to 90 %. Pores with the size above 100  $\mu\text{m}$  could be formed by glycine particles addition (Fig. 1), but porous HA ceramics prepared at the temperatures below 80 °C were composed of irregular shaped HA particles. In the contrast, the homogeneous porous structure for both macro-pores and micro-pores was observed for the samples treated at the temperatures above 105 °C. Porous HA ceramics prepared hydrothermally at 105 °C was composed of rod-shaped crystals elongated along the c-axis by SEM observation. The HA crystals were about 10  $\mu\text{m}$  in length with the mean aspect ratio of 40. The HA crystals expose a lot of crystal face [17],

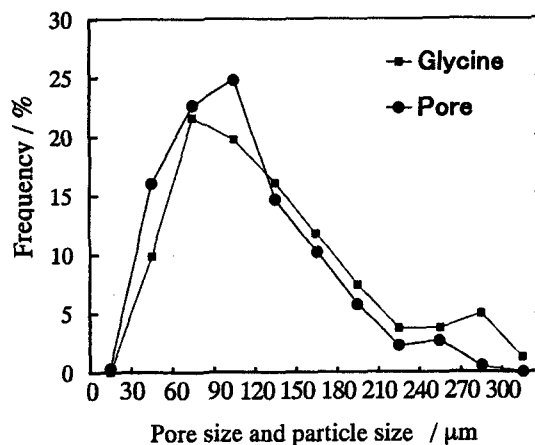


Fig. 1 Pore size distribution of porous ceramics of hydroxyapatite and particle size distribution of glycine as the additive.

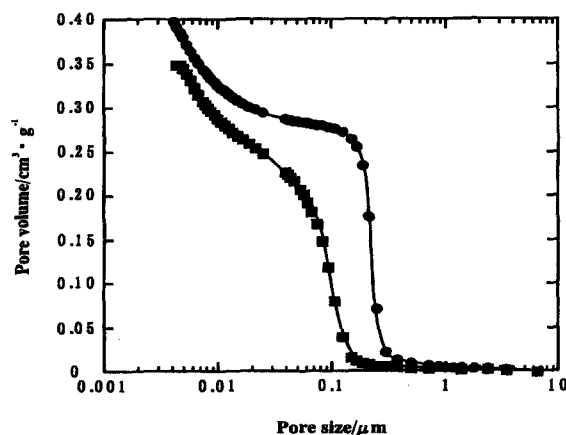


Fig. 2 Pore size distribution of porous ceramics of hydroxyapatite (■) and  $\beta$ -tricalcium phosphate (●).

therefore this porous HA ceramics must have the advantage of adsorptive activity. Rod-shaped crystals were locked together to make micro-pores. The distribution of micro-pore size measured by MIP is shown in Fig. 2. The mean diameter of micro-pore was 0.08  $\mu\text{m}$  in size. The porosity and the size of micro-pore increased slightly with increasing temperature of the hydrothermal treatment. The compressive strength of the porous HA with 70 % porosity prepared at 120 °C was about 2 MPa.

#### 3.2 Porous ceramics of $\beta$ -tricalcium phosphate

Calcium deficient HA tends to decompose into tricalcium phosphates by heating in comparison

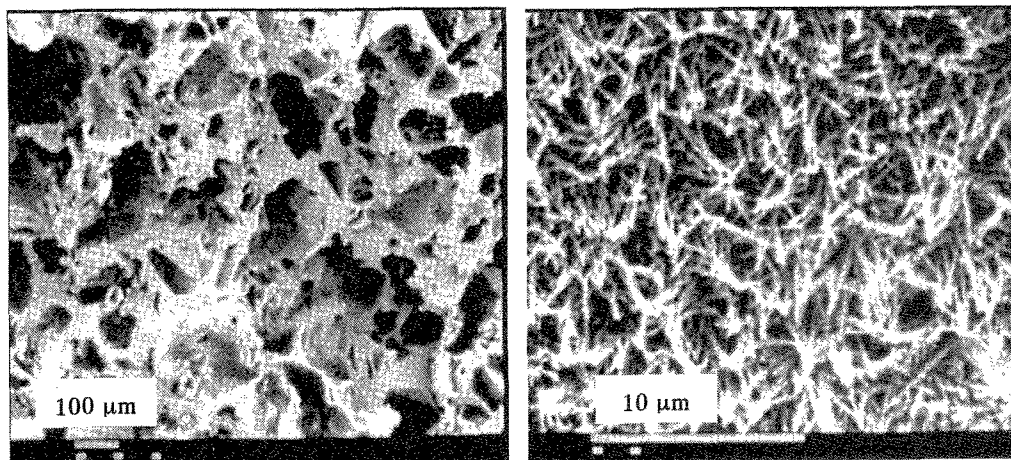


Fig. 3 SEM photographs of porous  $\beta$ -TCP ceramics with 70 % porosity with the bimodal pore structure. Macro-pores of over 100  $\mu\text{m}$  (the left) and micro-pores of about 0.2  $\mu\text{m}$  (the right) were observed.

with stoichiometric HA [14, 18]. Thus, porous ceramics of  $\beta$ -tricalcium phosphate ( $\beta\text{-Ca}_3(\text{PO}_4)_2$ :  $\beta$ -TCP) were obtained from the porous ceramics of calcium deficient HA with Ca/P ratio of 1.50 by heating it at 900  $^\circ\text{C}$  for 3 h in air. This porous  $\beta$ -TCP had almost the same micro-structure in comparison with the porous HA before heating. The porous  $\beta$ -TCP was composed of rod-shaped particles with about 10  $\mu\text{m}$  in length, and it had almost same porosity as the samples before heating (Fig. 1). The size of macro-pores of  $\beta$ -TCP was almost same as that of HA. The mean diameter of micro-pore of  $\beta$ -TCP ceramics was slight larger than that of HA ceramics, the value was about 0.2  $\mu\text{m}$  in size (Fig. 2). The compressive strength of the porous material increased by heating at 900  $^\circ\text{C}$  for 3 h in air. The compressive strength of the porous  $\beta$ -TCP with 70 % porosity was about 5 MPa.

Porous  $\beta$ -TCP with much amount of micro-pores prepared in this study should be more bio-degradable than the conventional materials. These porous ceramics must be suitable for the bone graft material and the scaffold of cultured bone. It is considered that the implant *in vivo* is probably first coated with plasma proteins and blood coagulation materials before cells adhesion take place, therefore micro-pores must effect the osteointegration process because such pores are similar in size to that of proteins. The micro-pores must make the protein adhesion to the materials surface [19].

#### 4. CONCLUSIONS

Porous ceramics of  $\beta$ -tricalcium phosphate with about 70 %-90 % porosity were prepared from the porous ceramics of calcium deficient hydroxyapatite by heating them at 900  $^\circ\text{C}$  for 3 h in air. These ceramics were composed of rod-shaped particles of about 10  $\mu\text{m}$  in length, and had much amount of micro-pores. This ceramics had the bimodal pore structure with macro-pores of over 100  $\mu\text{m}$  in size and with micro-pores of about 0.2  $\mu\text{m}$  in size. The macro-pores can promote the bone ingrowth, whereas the micro-pores can be filled with proteins.

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