

## Porous Apatite Ceramics Prepared by Hydrothermal Method

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Hydrothermal vapor treatment method was applied for preparation of ceramic biomaterials. Hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ; HA) ceramics with random crystal surface have already been used as bone-repairing materials which can directly bond to natural bones. If materials of HA could have the tailored specific crystal surface, they should have the advantage of adsorptive activity and osteoconductivity in comparison with the sintered HA. In the present study, porous HA with tailored crystal surface were prepared by the hydrothermal vapor exposure method at temperatures below 200 °C. Porous plates and granules of HA with controlled surface should be suitable for scaffold of cultured bone, for bone graft material and for drug delivery system (DDS).

### 1. Introduction

Hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ; HA) is known as major component of human hard tissue such as bones and teeth. Sintered HA has already been used as a bone-repairing material which can directly bond to natural bones in bony defect. It has been known to be biocompatible and osteoconductive [1], but newly bone formation on HA is not quick in comparison with the autograft. If materials of HA could have the tailored specific crystal surface, they should have the quick bone formation because of the advantage of adsorptive activity.

The authors reported various kinds of HA materials prepared by the unique hydrothermal methods [2-8]. In the present investigation, porous HA plates of about 50  $\mu\text{m}$  to 1 mm in thickness and porous HA granules of about 50  $\mu\text{m}$  to 1 mm in size with tailored crystal surface were prepared by the hydrothermal vapor exposure method [9-12]. This hydrothermal method is the strong technique for control the crystal surface.

The plates and granules of HA must be suitable as scaffold for cultured bone, for bone graft material, and for drug delivery system (DDS).

### 2. Experimental Methods

**2.1. Preparation of HA Plates** Commercial powders of  $\alpha$ -tricalcium phosphate ( $\alpha$ - $\text{Ca}_3(\text{PO}_4)_2$ :  $\alpha$ -TCP, Taihei Chemical Industrial Co., Ltd., Japan) and polyvinyl alcohol (PVA, Wako Pure Chemical Industries Ltd., Japan) were used as the starting materials. The slurry of  $\alpha$ -TCP with PVA was

prepared by using 10 mass% PVA aqueous solution at room temperature. To remove bubbles, the slurry was kept under vacuum condition. Films of  $\alpha$ -TCP with PVA were prepared from this slurry by spin overcoat method. This method is very popular technique to preparing polymer film. The glass dish was set on the turntable, and then the slurry was cast in the glass dish and twiddled. Films of  $\alpha$ -TCP with PVA were dried at room temperature for 12 h. In order to control the thickness of films, rotation speed was controlled. After heating at 1200 °C for 1 h in air, the samples were set in a 105 cm<sup>3</sup> autoclave (Fig. 1) with 30 cm<sup>3</sup> of pure water, and then they were exposed to vapor of the pure water at the temperatures from 105 to 200 °C under the saturated vapor pressure for 20 h.

**2.2. Preparation of HA Granules** 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 10 mass% gelatin (Wako Chemical Co., Japan) aqueous solution, the obtained slurry was dispersed in the vegetable oil at 70 °C, and then stirred at the rate of 0-900 r.p.m. in order to controlling of granules size. The samples were filtered off to recover, washed with ethanol, and dried at 105 °C in air. After heating at 1200 °C for 1 h in air, the samples were treated hydrothermally by the same method described above section of 2.1.

**2.3. Characterization** The produced phases were identified by powder X-ray diffractometry with

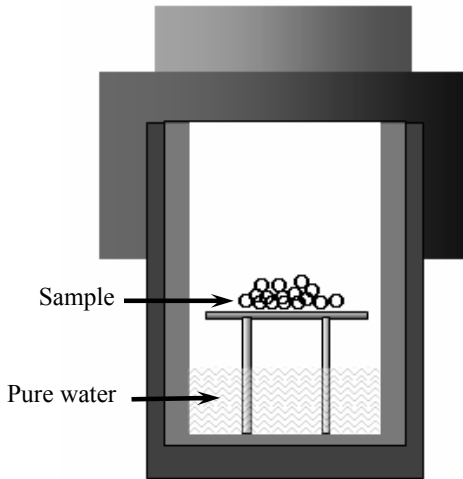


Fig. 1. Schematic illustration of the reaction apparatus.

graphite-monochromatized  $\text{CuK}\alpha$  radiation, operating at 40 kV and 20 mA (XRD; Rigaku, Geiger flex 2027, Japan). The samples prepared were dissolved in  $0.1 \text{ mol} \cdot \text{dm}^{-3}$  nitric acid, 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 (SEM; JEOL, JSM-T300, Japan). Pore volume and distribution of pore diameter were measured by mercury intrusion porosimetry (MIP; Carlo Elba, Porosimeter 2000, Italy).

### 3. Results and Discussion

**3.1. HA Plates** The thickness of  $\alpha$ -TCP film was controlled from about  $50 \mu\text{m}$  to about  $1 \text{ mm}$  by controlling of rotation speed. The mixture film of  $\alpha$ -TCP and PVA could be made into a convenient form. To remove PVA and keep crystal phase as  $\alpha$ -TCP, the mixture of  $\alpha$ -TCP and PVA film was heated at  $1200 \text{ }^\circ\text{C}$  for 5 min in air. The shape of plates did not change and handling of the sample was not difficult. From X-ray diffraction, there were no phases other than  $\alpha$ -TCP.

Using hydrothermal vapor exposure method [9-12],  $\alpha$ -TCP changes into HA and the sample is hardened because of hydration of  $\alpha$ -TCP [13]. Fig. 2(A) shows the HA plate prepared by hydrothermal

treatment at  $120 \text{ }^\circ\text{C}$  for 3 h under saturated vapor pressure. The porosity of HA plate was about 75 % and specific surface area was about  $30 \text{ m}^2/\text{g}$ . HA plate prepared by hydrothermal treatment at  $120 \text{ }^\circ\text{C}$  for 30 min was composed of rod-shaped crystals elongated along the  $c$ -axis by SEM observation (Fig. 2 (B)). The rod-shaped crystals were about  $20 \mu\text{m}$  in length with aspect ratio of about 10 and locked together to make micro-pores. The size of micro-pores increased gradually with the hydrothermal treatment period. The plate of  $\alpha$ -TCP completely changed into HA at  $120 \text{ }^\circ\text{C}$  under saturated vapor pressure for the period over 3 h. From X-ray diffraction, the HA plate after heating at  $900 \text{ }^\circ\text{C}$  for 3 h in air contained HA and  $\beta$ -TCP. The relative intensity of XRD lines for HA and for  $\beta$ -TCP was used in order to determine the HA and  $\beta$ -TCP contents and then the Ca/P molar ratio of samples was estimated [14, 15]. The value of Ca/P of the HA plate prepared by hydrothermal treatment at  $120 \text{ }^\circ\text{C}$  for 3 h was 1.51, that was lower than Ca/P of stoichiometric HA (Ca/P=1.67). Chemical analysis by ICP-MS gave the same value of Ca/P. This HA was calcium deficient hydroxyapatite.

**3.2. HA Granules** Spherical mixture of  $\alpha$ -TCP and gelatin were obtained after dropping slurry into the vegetable oil. Gelatin was observed among the particles of  $\alpha$ -TCP. The size of spherical particles could be controlled by the control of stirring rate. The size of particles decreased with increasing stirring rate. After heating at  $1200 \text{ }^\circ\text{C}$  for 1 h, gelatin was burned out and no other phases than  $\alpha$ -TCP were revealed by XRD. The XRD pattern of the sample after hydrothermal treatment shows high crystallinity of HA and no existence of phases other than HA.

Microstructure-designed HA granules from about  $50 \mu\text{m}$  to  $1 \text{ mm}$  in size could be prepared by hydrothermal vapor exposure method at the temperatures from  $105$  to  $200 \text{ }^\circ\text{C}$  under saturated vapor pressure of pure water. The spherical HA granule prepared hydrothermally at  $160 \text{ }^\circ\text{C}$  for 3 h is shown in Fig. 3. The size of HA granule (A) is larger than that of HA granule (B). The size of granules could be controlled by the control of stirring rate. The granular HA was composed of rod-shaped crystals of about  $20 \mu\text{m}$  in length with the mean aspect ratio of 30 (Fig. 4). Rod-shaped HA crystals were not obtained below  $70 \text{ }^\circ\text{C}$ . These crystals were elongated along the  $c$ -axis according to TEM analysis. Rod-shaped HA crystals were locked together to make micro-pores of about  $0.1$

$\mu\text{m}$  in size. It was non-stoichiometric HA with calcium deficient composition of  $\text{Ca/P} < 1.60$  according to ICP-MS analysis. The value of Ca/P molar ratio of rod-shaped HA particles prepared hydrothermally at the indicated temperatures for 5 h was shown in Fig. 5.

These granular HA must have the advantage of

adsorptive activity in comparison with the reported materials [16, 17], because the HA has large specific crystal surface and micro-pores. Microstructure designed HA granules with controlled surface must be suitable for drug delivery system (DDS), for scaffold of cultured bone and for bone graft material.

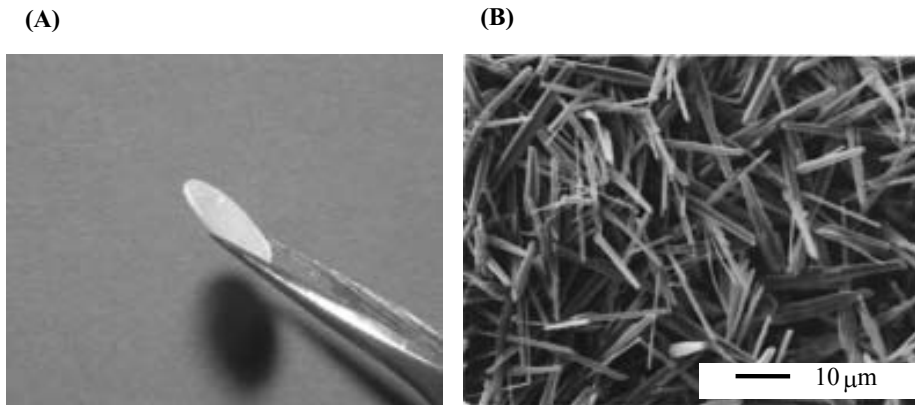


Fig. 2. Plate of HA prepared by hydrothermal method at 120 °C under saturated vapor pressure for 3 h (A). Rod shaped crystals were observed by SEM (B).

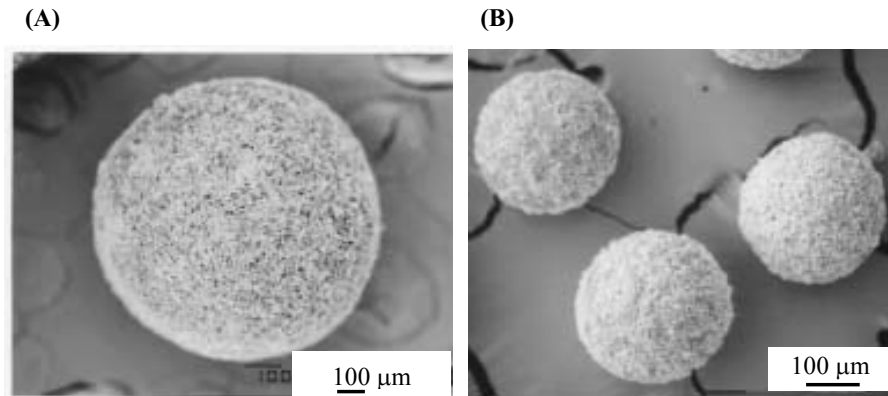


Fig. 3. Scanning electron micrographs of the HA granule prepared by hydrothermal vapor exposure method. (A) The stirring rate was 0 r.p.m. (B) The stirring rate was 300 r.p.m.

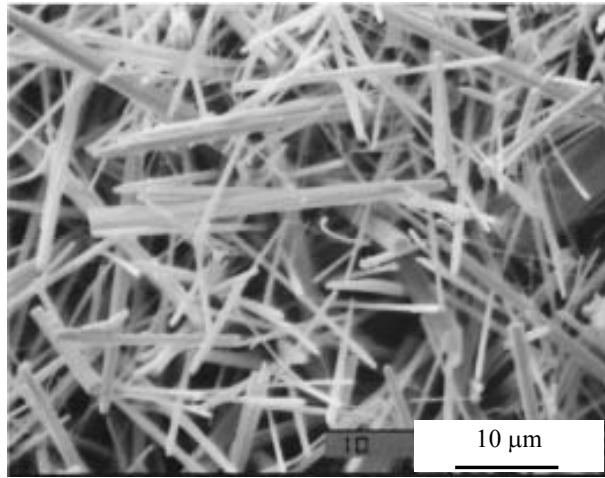


Fig. 4. Scanning electron micrograph of the HA granule prepared by hydrothermal vapor exposure method as shown in Fig. 3 (A).

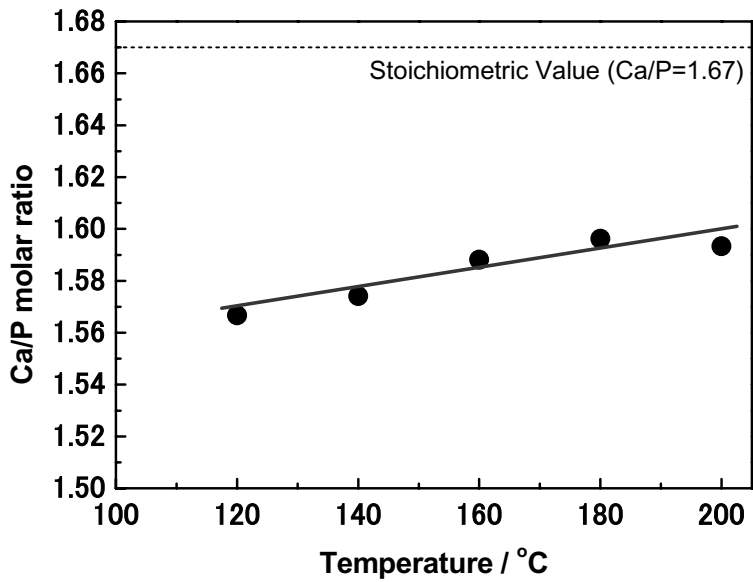


Fig. 5. Ca/P molar ratio of rod-shaped HA particles prepared by hydrothermal vapor exposure method at the indicated temperature for 5 h.

#### 4. Conclusions

The results described in this paper allow us to draw the following conclusions:

- (1) Hydrothermal vapor treatment method is the strong technique for controlling the crystal surface.
- (2) Rod-shaped crystals of HA with Ca deficient composition with Ca/P<1.67 could be synthesized under hydrothermal conditions.
- (3) Porous HA plates with about 50  $\mu\text{m}$  to 1 mm in thickness composed of rod-shaped crystals were prepared by the hydrothermal vapor exposure method.
- (4) Porous HA granules of about 50  $\mu\text{m}$  to 1 mm in size composed of rod-shaped crystals were prepared by the hydrothermal vapor exposure method.
- (5) These HA materials must have the advantage of adsorptive activity, because they had large specific crystal surface of *a*-face and micro-pores.

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#### References and Notes

- [1] For example, *Bioceramics* **16**, ed. F.J. Monterio, R. Correia, B. Leon, Trans Tech Publications (2003).
- [2] K. Ioku, M. Yoshimura and S. Somiya, *Bioceramics* **1**, Ishiyaku EuroAmerica, Tokyo and St. Louis (1989) p. 62
- [3] K. Ioku, M. Yoshimura and S. Somiya, *Biomaterials*, **11** 57 (1990).
- [4] K. Ioku, M. Yoshimura and S. Somiya, *Phosphorus Res. Bull.*, **1** 15 (1991).
- [5] M. Yoshimura, H. Suda, K. Okamoto and K. Ioku, *J. Mater. Sci.*, **29** 3399 (1994).
- [6] K. Ioku, K. Yamamoto, K. Yanagisawa and N. Yamasaki, *Phosphorus Res. Bull.*, **4** 65 (1994).
- [7] K. Ioku, A. Oshita, H. Fujimori, S. Goto and M. Yoshimura, *Trans. Mater. Res. Soc. Japan*, **26** 1243 (2001).
- [8] K. Ioku, S. Yamauchi, H. Fujimori, S. Goto and M. Yoshimura, *Solid State Ionics*, **151** 147 (2002).
- [9] K. Ioku, S. Nishimura, Y. Eguchi and S. Goto, *Rev. High Pressure Sci. Technol.*, **7** 1398 (1998).
- [10] K. Ioku, M. Fukuhara, H. Fujimori and S. Goto: *Korean J. Ceram.*, **5** 115 (1999).
- [11] K. Ioku, H. Misumi, H. Fujimori, S. Goto and M. Yoshimura, *Proc. 5th Int. Conf. Solvo-Thermal Reactions* (Rutgers, The State Univ. of NJ, USA 2002), p.233
- [12] K. Ioku, M. Toda, H. Fujimori, S. Goto and M. Yoshimura, *Key Engineering Materials*, **254-256** (Bioceramics Vol.16) 19 (2004).
- [13] H. Monma and T. Kanazawa, *J. Ceram. Soc. Japan*, **84** 209 (1976).
- [14] K. Ioku, T. Murakami, Y. Ikuma, and M. Yoshimura, *J. Ceram. Soc. Japan Int. Edition*, **100** 1015 (1992).
- [15] K. Ishikawa, P. Ducheyne and S. Radin, *J. Mater. Sci.: Mater. Med.*, **4**, 165-168 (1993).
- [16] W. Paul and C. P. Sharma, *J. Mater. Sci.: Mater. Med.*, **10** 383 (1999).
- [17] V. S. Komlev and S. M. Barinov, *J. Mater. Sci.: Mater. Med.*, **13** 295 (2002).