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Preparation of hydroxyapatite by the hydrolysis of brushite

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The conversion of brushite ($CaHPO_4 \cdot 2H_2O$; DCPD) into hydroxyapatite (HAp) by hydrolysis has been studied by separating the conversion process into two stages, i.e. the structural change of DCPD into HAp (I) and the subsequent compositional increase in Ca/P ratio of the HAp (II). In Reaction I at 40° C, HAp formed most rapidly at around pH 7.5 to 8.0. The complete conversion was observed within 2.5 h at 40° C, 1 h at 60° C and only 5 min at 80° C. The compositions of HAp thus formed were nonstoichiometric and had a Ca/P ratio below 1.60. It was difficult to increase the Ca/P ratio up to the stoichiometric value 1.67, because the adjustment of pH to higher values and/or the addition of Ca^{2+} ions to accelerate the increase in Ca/P ratio, retarded the proceeding of Reaction I. On the other hand, in Reaction II, such pH adjustment and Ca^{2+} addition were remarkably effective in increasing the Ca/P ratio. Consequently, two-stage processing was reasonable and convenient for the preparation of stoichiometric HAp, because it was possible to manage the controlling factors in both Reactions I and II independently. The resulting HAp powders showed a comparatively low crystallinity similar to precipitated HAp and large weight losses (above 6%) on heating, and were composed of dense aggregates of irregular thin microcrystals.

1. Introduction

Hydroxyapatite (HAp), with compositions of stoichiometric $Ca_{10}(PO_4)_6(OH)_2$; $Ca/P = 1.67$ and nonstoichiometric $Ca_{10-x}(HPO_4)_x(PO_4)_{6-x}(OH)_{2-x} \cdot nH_2O$; $Ca/P < 1.67$, is of considerable interest as an excellent material for artificial bones and teeth, chromatographic separation of bio-macromolecules and suspension polymerization of styrene. HAp powders for such applications are normally prepared by precipitation and hydrolysis methods, but characteristics of HAp powder thus prepared show a sensitive dependence on preparation conditions, e.g. the reaction system used, starting materials, pH, temperature, ripening time, calcination temperature, etc.

In this work the preparation of HAp by the hydrolysis of brushite ($CaHPO_4 \cdot 2H_2O$; DCPD) was studied on the basis of the following two-stage scheme,

$$\mathrm{DCPD} \xrightarrow{\mathrm{I}} \mathrm{HAp}(\mathrm{Ca/P} < 1.67) \xrightarrow{\mathrm{II}} \mathrm{HAp}(\mathrm{Ca/P} = 1.67)$$

with the purpose of higher simplicity and productivity than the conventional one-stage processing DCPD → HAp(Ca/P = 1.67). Reaction I corresponds to a structural change into the apatite structure and Reaction II a compositional increase in Ca/P ratio retaining the apatite structure. The resulting HAp powders were characterized by Ca/P ratio, X-ray diffraction, thermogravimetric (TG) loss and scanning electron microscopic (SEM) observation.

2. Experimental procedure

Reagent-grade DCPD was used as the starting material. $CaHPO_4$ (DCPA) and α-$Ca_3(PO_4)_2$ (α-TCP) used for comparison were prepared by heating DCPD at 200° C for 1 h, and by heating an equimolar mixture of γ-$Ca_2P_2O_7$ (thermally synthesized from DCPD at 550° C for 2 h) and reagent $CaCO_3$ at 1200° C for 1 h, respectively. In Reaction I, 1.0 g DCPD was suspended and stirred in 100 ml distilled water by bubbling nitrogen gas and using a magnetic stirrer. The reaction temperature and pH were kept within the ranges 40 to 80° C and 6 to 13, respectively, during the hydrolysis. The reaction pHs were adjusted with ammonium hydroxide or tetramethylammonium hydroxide ($(CH_3)_4NOH$) solution. Solid products were filtered, washed with water and dried at 80° C. In Reaction II, HAp(Ca/P = 1.50) prepared by the hydrolysis of 50 g DCPD in 250 ml water at pH 8 and 40° C for 4 h was used, and the HAp(Ca/P = 1.50) of 1.0 g powder sample was treated at 30 to 50° C for 1 h in 100 ml alkaline solutions containing 0.2 g $CaCl_2 \cdot 2H_2O$ as a reaction accelerator. The resulting products were filtered, washed and dried in the same manner as above. Precipitated HAp was prepared by keeping a mixture of equivolumes of 0.24 M $(NH_4)_2HPO_4$ solution and 0.4 M $Ca(OH)_2$ aqueous suspension at 40° C for 1 h by stirring and bubbling nitrogen gas, then centrifuging and drying at 80° C. The analysis of Ca/P ratio of HAp was carried out on the following basis:

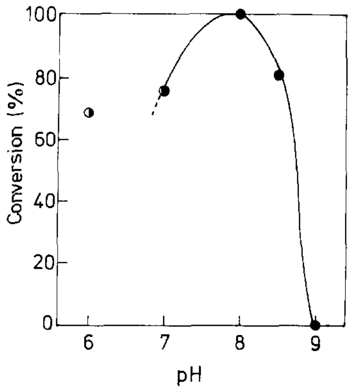

Figure 1 Hydrolysis of DCPD into HAp (40° C, 3 h). Product: (●) HAp(Ca/P = 1.50), (◐) HAp(Ca/P = 1.50) + $Ca_8H_2(PO_4)_6 \cdot 5H_2O$.

HAp(Ca/P < 1.67) decomposes at about 800° C to a two-phase mixture of HAp(Ca/P = 1.67) and TCP corresponding to the Ca/P ratio. Then the Ca/P ratio was estimated from relative amounts of the two phases. The relative amounts were determined by X-ray diffraction. X-ray powder diffraction patterns were measured using a Toshiba diffractometer using Cu*Kα* radiation. TG measurements were recorded up to 900° C with a heating rate of $10° C\,min^{-1}$ in quiescent air using a Shinku Riko TA-1500. SEM observation was made using a Nippon Denshi JSM-50A.

3. Results and discussion

3.1. Hydrolysis of DCPD (Reaction I)

Hydrolysis reactions at 40° C for 3 h were as follows: no conversion at pH 9, conversion into HAp at pH 8.5 to 7.0 and into octacalcium phosphate ($Ca_8H_2(PO_4)_6 \cdot 5H_2O$) at pH 6. The conversion into HAp was most rapid at around pH 7.5 to 8.0 as shown in Fig. 1. Hydrolysis times for the complete conversion were within 2.5 h at 40° C, 1 h at 60° C and only 5 min at 80° C. Above 60° C the complete conversion was performed within 1 h at pH 7 to 9. Ca/P ratios of HAp thus obtained varied with reaction time as shown in Fig. 2. The higher the pH and temperature were, the more easily was the Ca/P ratio increased up to about 1.60 (which seemed to be an upper limit in this reaction system). Such increases in the Ca/P ratio must be related to ease of release of PO_4^{3-} ions from the solid phase to the liquid phase at high pHs and temperatures. In order to accelerate the rate of increase in Ca/P ratio, the addition of Ca^{2+} ions to hydrolysis system I was attempted, however, the coexistence of Ca^{2+} ions resulted in extreme retardation of the conversion of DCPD as shown in Fig. 3, probably because of a suppression effect on the dissolution of DCPD as well as in the hydrolysis of α-TCP [1].

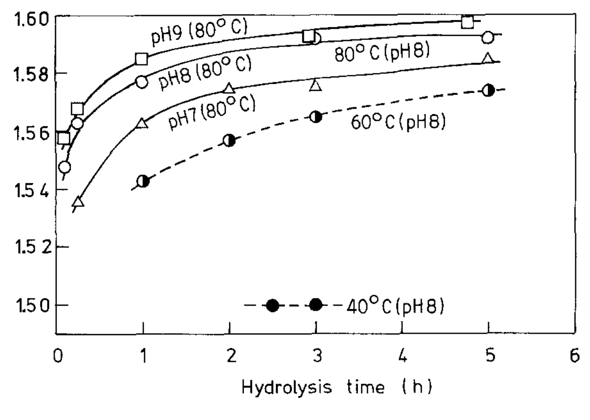

Figure 2 Time-dependence of Ca/P ratio of HAp formed in Reaction I as a function of pH and temperature.

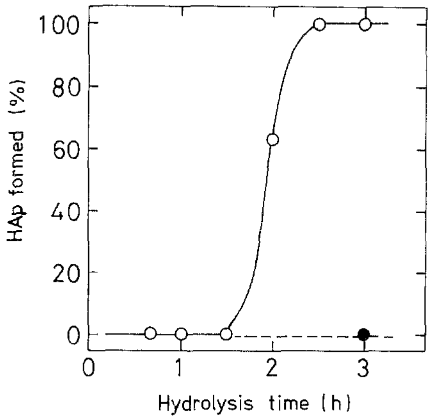

Figure 3 Conversion of DCPD into HAp (●) with and (○) without addition of Ca^{2+} ions in Reaction I (40° C, pH 8).

3.2. Reaction II

Reaction II consists of the process of increasing the Ca/P ratio of HAp(Ca/P = 1.50) through further release of PO_4^{3-} ions from the HAp or Ca^{2+} uptake coupled with OH^- uptake and H_2O release depending on the non-addition or addition of Ca^{2+} ions to the system. In practice, Reaction II was carried out in alkaline solutions with the addition of $CaCl_2 \cdot 2H_2O$ as a Ca^{2+} source for an increase in the Ca/P ratio. Fig. 4 shows relationships between pH and Ca/P ratio of HAp as a function of temperature (reaction time: 1 h). The addition of 0.2 g $CaCl_2 \cdot 2H_2O$ is sufficient to increase the Ca/P ratio of 1.0 g HAp(Ca/P = 1.50) up to 1.67. The stoichiometric ratio was obtained at 40° C after 3 h in runs at pH 9 to 10, and after 1 h at pH 13.

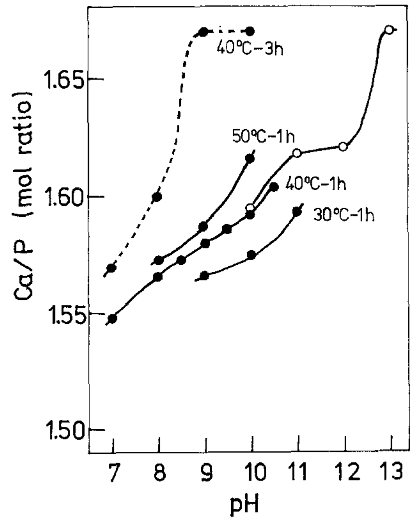

Figure 4 Increases in Ca/P ratio of HAp(Ca/P = 1.50) in solutions containing Ca^{2+} ions (0.2 g $CaCl_22H_2O$/1.0 g HAp). pH adjustment: (●) with NH_4OH, (○) with $(CH_3)_4NOH$.

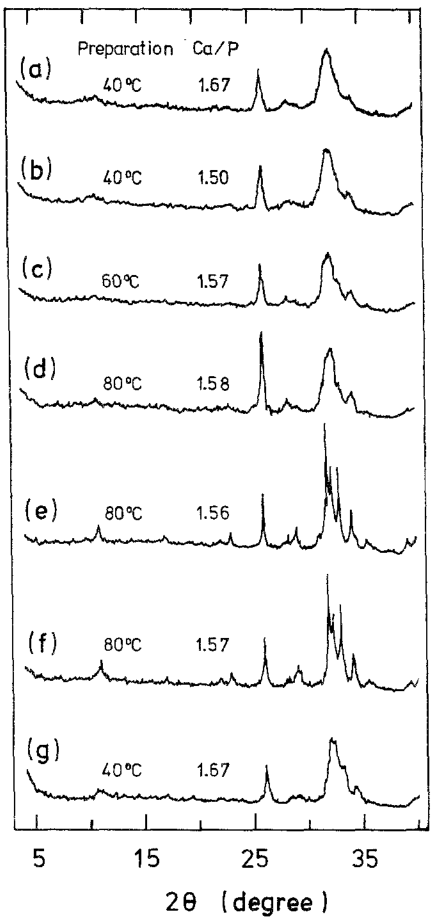

Figure 5 X-ray diffraction patterns of HAp samples prepared by hydrolysis of (a to d) DCPD, (e) α-TCP and (f) DCPA, and (g) by precipitation from solution.

3.3. Crystallinity

Fig. 5 shows the X-ray diffraction patterns for HAp samples giving a comparison of crystallinity. HAp samples prepared by the hydrolysis of DCPD had a low crystallinity similar to that of precipitated HAp (Fig. 5g), regardless of variation in the Ca/P ratio (Figs 5a and b) and hydrolysis temperature (Figs 5c and d). On the other hand HAp samples from different starting materials, i.e. DCPA and α-TCP, showed comparatively high crystallinities (Figs 5e and f). Such a difference in crystallinity might be associated with the fact that the hydrolysis of DCPD and precipitation of HAp from solution are far easier than the hydrolyses of DCPA and α-TCP.

3.4. SEM observation

Generally, the appearance of HAp powders prepared by hydrolysis tends to take over powder shapes of the starting materials. Fig. 6 shows scanning electron micrographs of HAp powders prepared from different shaped starting materials: DCPD platelets (A_1, A_2), α-TCP granules (C_1) and DCPA platelets (B_1, B_2) with a wrinkled surface. HAp powders (A_3) prepared from DCPD were composed of dense aggregates of irregular thin microcrystals, HAp (C_3) prepared from α-TCP were porous aggregates of needle-like crystals and HAp (B_3) prepared from DCPA were platelet aggregates of entangled needle-like crystals. In all cases the resulting morphology reflected the original powder shapes.

TABLE I Intermediate formation of α-TCP in the course of heating of HAp(Ca/P = 1.58)

Temperature (°C)	Phase by X-ray diffraction*
Room temperature	apatite
700	apatite
750	apatite
770	apatite, α-TCP
800	apatite, α-TCP, β-TCP
850	apatite, α-TCP, β-TCP
900	apatite, β-TCP, α-TCP

*After heating up to each temperature at 10° C min^{-1} and cooling rapidly to room temperature.

3.5. Thermal changes

Details of structural, compositional and dehydration changes of HAp on heating are studied in detail [2–5]. Here, two features associated with HAp(Ca/P < 1.67) were described in the following way. HAp(Ca/P < 1.67) produced an intermediate, high-temperature form of TCP, i.e. α-TCP, below its transition temperature of 1180° C (Table I). A similar fact has already been found in the cases of precipitated HAp(Ca/P < 1.67) [6] and amorphous calcium phosphate ($Ca_3(PO_4)_2 \cdot xH_2O$) [7–9]. The appearance of the α-form suggested that thermal decomposition processes of HAp(Ca/P < 1.67) might involve a local or transient amorphous state. Weight losses on heating HAp(Ca/P < 1.67), i.e. amounts of liberated H_2O, generally increase as the Ca/P ratio of HAp decreases [2, 5]. However, when preparation conditions for HAp were altered, remarkable differences in heating weight loss were observed even if HAp samples had a similar Ca/P ratio. Fig. 7 shows TG curves for HAp samples prepared under different conditions. Weight losses up to 700° C are due to H_2O liberation whilst retaining the apatite structure, and the substantial losses between 750 and 850° C are due to the conversion of HAp(Ca/P < 1.67) into HAp(Ca/P = 1.67) + TCP [5, 10], which is a characteristic of nonstoichiometric HAp. Assuming that weight losses of HAp (Ca/P = 1.67) were due to the desorption of bound H_2O on the surface of HAp powders, these HAp powders must be extremely fine. HAp prepared from DCPD had features such as comparatively large weight losses on heating and an opposite relationship to the usual one [5] between weight loss and Ca/P ratio. Namely, Reaction II was considered to alter HAp powders formed in Reaction I into finer powders with increasing Ca/P ratio.

4. Conclusions

1. Efficient preparation of stoichiometric hydroxyapatite was carried out by two-stage hydrolysis of DCPD: (I) a structural change into apatite and (II) a compositional increase in Ca/P ratio of the apatite.

2. Reaction I proceeded optimally at around pH 7.5 to 8.0. The adjustment of pH to higher values and/or the addition of Ca^{2+} ions which were expected to increase the reaction rate and the Ca/P ratio of apatite, did not prove to do so. Reaction II was accelerated by increases in pH and/or by the addition of Ca^{2+} ions.

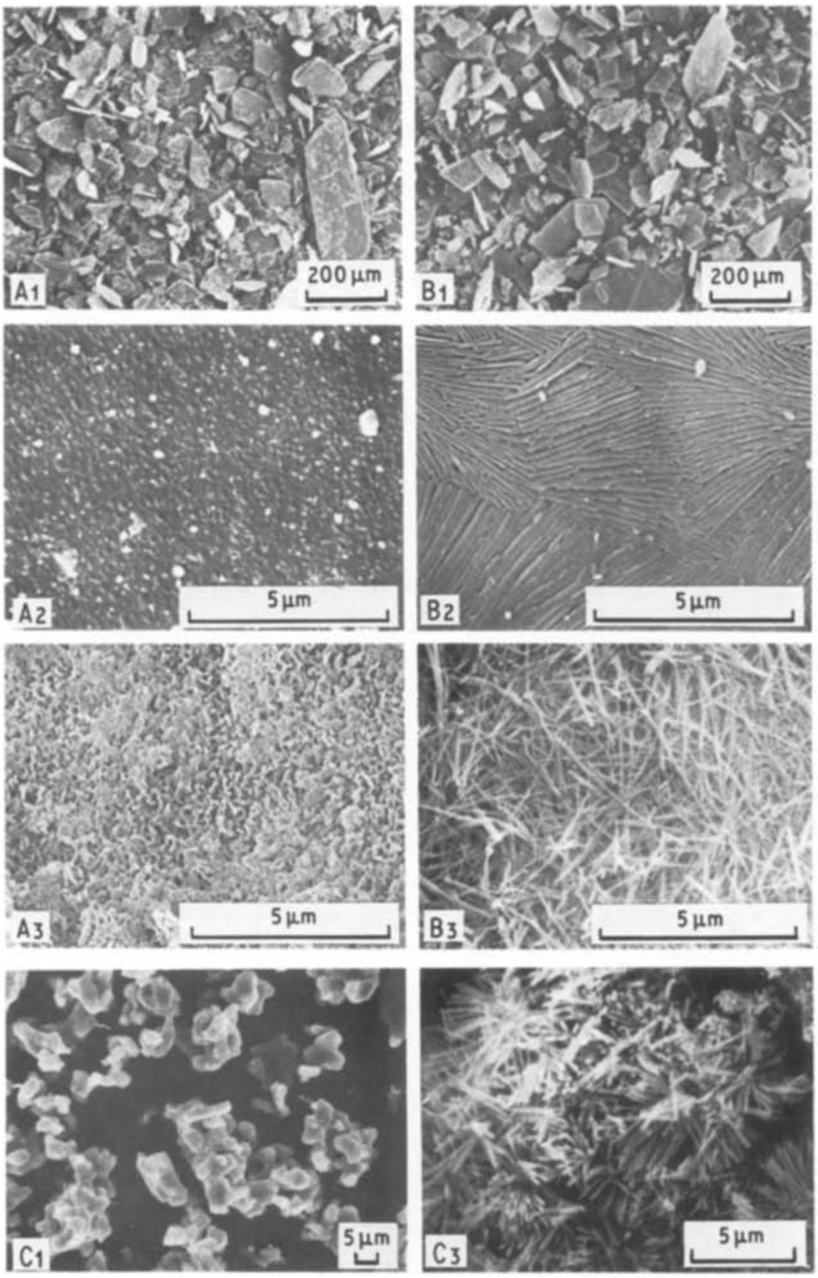

Figure 6 Scanning electron micrographs of starting powders and HAp powders during their hydrolyses. A_1, B_1 and C_1: DCPD, DCPA and α-TCP powders. A_2 and B_2: surface textures of DCPD and DCPA powders. A_3, B_3 and C_3: HAp prepared from DCPD, DCPA and α-TCP.

3. The resulting apatites showed comparatively low crystallinity, contained large amounts of thermally volatile H_2O, and were composed of dense aggregates of irregular thin microcrystals.

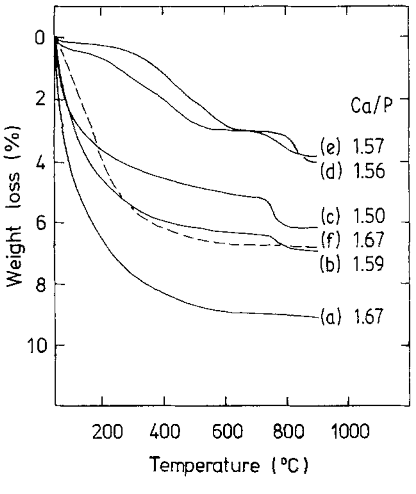

Figure 7 TG curves for HAp prepared by hydrolyses of (a to c) DCPD, (d) α-TCP and (e) DCPA, and (f) by precipitation.

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