Wet preparation of calcium phosphates from aqueous solutions

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Abstract. Calcium phosphates such as HA (hydroxyapatite), β-TCP (tricalcium phosphate) and biphasic HA/β-TCP, were synthesized by wet chemical precipitation in aqueous solution combined with ball milling process. Nanosize powders of the calcium phosphates were synthesized using $Ca(OH)_2$ and H_3PO_4. The effects of initial precursor Ca/P ratio (1.30, 1.50 and 1.67), ball milling process and post heat-treatment on the phase evolution behavior of the powders were investigated. The phase of resulting powder was controllable by adjusting the initial Ca/P ratio. HA was the only phase for as-prepared powders in both cases of Ca/P ratios of 1.50 and 1.67. The single HA phase without any noticeable second phase was obtained for the initial Ca/P ratio of 1.67 in the overall heat-treatment range. Pure β-TCP and biphasic calcium phosphate (HA/β-TCP) were synthesized from precursor solutions having Ca/P molar ratios of 1.30 and 1.50, respectively, after having been heat-treated above 700 ºC. The β-TCP phase has appeared on the pre-existing DCPD (dicalcium phosphate dihydrate) and/or HA phase. Dense ceramics having translucency were obtained at a considerably lower sintering temperature. The modified process offered a fast, convenient and economical route for the synthesis of calcium phosphates.

Keywords: Calcium phosphate, Hydroxyapatite, Tricalcium phosphate, Nanopowder, Wet chemical synthesis.
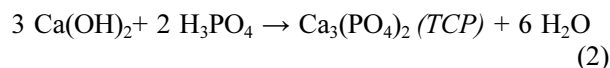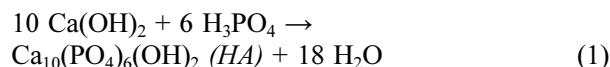
Introduction

Calcium phosphates have been widely utilized in biological applications. Among the calcium phosphates, significant attention has been given to hydroxyapatite (HA, $Ca_{10}(PO_4)_6(OH)_2$) and tricalcium phosphate (β-TCP, $Ca_3(PO_4)_2$) due to their prominent bioactivity and biocompatibility [1-4]. Over the past few decades, the biphasic calcium phosphate (BCP) composed of both the tricalcium phosphate (β-TCP) and hydroxyapatite (HA) has also received considerable attention due to its enhanced biocompatibility and mechanical properties [5-7].

Recently, nanometer-sized calcium phosphates have received much attention due to their significantly enhanced efficacy [1, 6]. Solution processes have been widely used to prepare nanometer-sized powders. Wet chemical precipitation using aqueous solutions is the most common synthesis route for the preparation of calcium phosphates nanoparticles, which provides additional advantageous features such as simple, low cost and low temperature synthesis [8-10].

Calcium hydroxide ($Ca(OH)_2$) and phosphoric acid (H_3PO_4) were widely used as starting materials for the precipitation process for HA and β-TCP preparation according to the reactions, Eq. (1) and (2), respectively. The only byproduct of the reactions is water, and the reactions involve no foreign elements.

$$10\ Ca(OH)_2 + 6\ H_3PO_4 \rightarrow$$
$$Ca_{10}(PO_4)_6(OH)_2\ (HA) + 18\ H_2O \qquad (1)$$

$$3\ Ca(OH)_2 + 2\ H_3PO_4 \rightarrow Ca_3(PO_4)_2\ (TCP) + 6\ H_2O \qquad (2)$$

The properties of particles prepared by the wet synthesis method are largely dependent on process parameters. The phase, size, shape, and surface area of the particles obtained by the wet process are highly sensitive to the precursor concentration, Ca/P ratio of precursors, and reaction pH [5, 11]. Furthermore, the phosphoric acid addition rate is strongly linked to the suspension stabilization, and also to the final precipitate (powder) properties [12, 13]. The precipitation chemistry for the preparation of calcium phosphates has been found to be complicated due to the slow attainment of equilibrium and the amorphous nature of the products formed. It is also very important to obtain a large amount of products at a constant reactant volume.

The present study deals with the modified synthesis of calcium phosphate powders using a wet precipitation method combined with mechanical ball milling process. In this study, calcium hydroxide was used as a calcium precursor and phosphoric acid was added as a source of phosphorus according to Eq. (1) and (2). This work is concerned with a more convenient approach to the preparation of calcium phosphate compounds such as pure β-TCP, biphasic calcium phosphate (HA/β-TCP) and pure HA, from precursor Ca/P molar ratios of 1.30, 1.50 and 1.67, respectively, using precursor solutions

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with higher concentrations than other wet preparation processes. In order to clarify the effect of precursor Ca/P ratio on the powder properties, this study has been carried out without any capping or pH control agents. Nanoscale calcium phosphate powders were synthesized via the precipitation process combined with a ball milling process, and the feasibility of the process for large-scale production at high production rates was discussed.

Experimental

Calcium phosphate nanoparticles were prepared by a wet precipitation route followed by ball milling process under controlled synthesis conditions. Calcium hydroxide $(Ca(OH)_2)$ and phosphoric acid (H_3PO_4) were used as precursors.

In the process, 85% of H_3PO_4 solution was added dropwise into 275 ml of a high concentration (1 M) of $Ca(OH)_2$ aqueous suspension solutions within 20 min. For the preparation of the different calcium phosphates, the predetermined Ca/P molar ratio of the solutions of 1.30, 1.50 and 1.67 was set by adding the H_3PO_4 solution to the continuously stirred $Ca(OH)_2$ suspension at room temperature. The precipitation products with the mother solution were ball milled at 250 revolutions per minute. After the ball milling process up to 12 h, the synthesized powders were dried at 60 °C for 12 h. Unlike other preparation processes for calcium phosphates, there was no maturing (aging) and filtering (washing) process involved.

The prepared powders were calcined at different temperatures ranging from 500 °C to 900 °C to study phase developments. The dried powders were formed to pellets, and then sintered at 1,100 °C for 2 h. The properties for the powders and sintered ceramics were characterized using scanning electron microscopy (SEM) and X-ray diffraction (XRD) using Cu Kα radiation ($\lambda = 1.5418$ Å). The particle sizes of the synthesized powders were also calculated by the XRD peak broadening according to the Scherrer's equation (D_{cal} (particle size) $= 0.89 \lambda/(B \cos \theta)$: where λ is the wavelength, B is the full width at half maxima (FWHM) in radians and θ is the diffraction angle).

Results and Discussion

In the present study, calcium phosphates such as β-TCP, biphasic calcium phosphate (HA/β-TCP) and HA were prepared by a new approach of the aqueous precipitation method, which was combined with mechanical ball milling process, from precursor Ca/P ratios of 1.30, 1.50 and 1.67, respectively. As the Ca/P ratio decreased from 1.67 to 1.30, the pH after the precipitation reaction decreased from 11.3 to 4.9, due to the lowered base/acid ratios in the solutions. Changes in the pH value of the solutions as-precipitated and

after the ball milling process are given in Table 1. The initial pH value of the solution after precipitation was measured to be 11.3 and the value decreased to 7.4 after the ball milling process for Ca/P molar ratio of 1.67. The pH values of biphasic HA/β-TCP also decreased from 10.0 to 7.8 at Ca/P molar ratio 1.5. This decrease in pH values was due to the completion of the chemical reactions of the unreacted precursors through the ball milling process forming HA (i.e. calcium phosphate-hydroxide) with consumption of free hydroxide (OH^-) in the reactant solution in accordance with Eq. (1). In contrast, for β-TCP powders from Ca/P molar ratio of 1.30, the pH value was increased from 4.9 to 6.5 with increasing ball milling time, because, after the precipitation reaction progressed, water having the higher pH value (~7) was formed from the lower pH precursor solution, following Eq. (2).

The effect of ball milling on the phase pure HA preparation is presented in Fig. 1. When the powder

Table 1. pH values with ball milling time of precipitated calcium phosphates powders with different precursor Ca/P ratios: Ca/P = 1.30, 1.50, and 1.67.

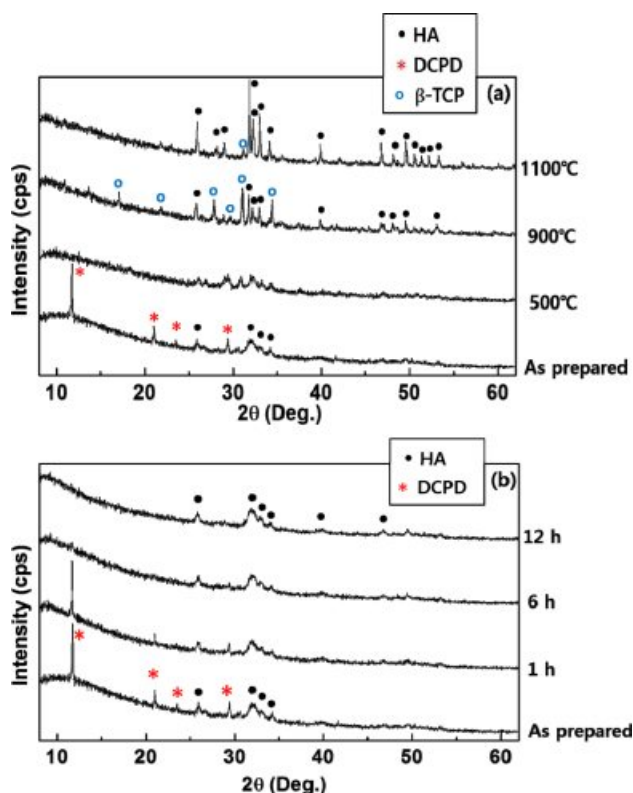| Samples	pH with ball milling time			
	As-prepared	1 h	6 h	12 h
Ca/P=1.67	11.3	10.9	7.7	7.4
Ca/P=1.50	10.0	8.9	7.9	7.8
Ca/P=1.30	4.9	5.8	6.5	6.5

Fig. 1. XRD patterns of synthesized HA powders from Ca/P = 1.67 prepared by (a) heat treatment at different temperatures and (b) ball milling process with various milling time.

was prepared in a short period of precursor mixing time within 10 min from Ca/P of 1.67, the predominant phase of the precipitate was mostly undesirable DCPD ($CaHPO_4 \cdot 2H_2O$ (JCPDS 11-293)). Once the DCPD appeared, the phase was quite stable. To turn the phase into the desired HA phase (hexagonal HA (JCPDS 9-432)), a heat-treatment up to 1,100 ℃ was required as shown in Fig. 1(a). Even after the high temperature heat treatment, it was difficult to obtain the phase pure HA. On the contrary, the phase pure HA phase can be synthesized by the simple ball milling process. As can be seen in Fig. 1(b), there was a drastic phase change from DCPD to HA by ball milling process. To prepare the single HA phase precipitate, about 6 hours of ball milling was required. On the other hand, the β-TCP phase (JCPDS 9-169) could not be easily synthesized by ball milling process using the precipitates from the precursor Ca/P ratios of 1.30 and 1.50, and subsequent heat treatment was necessary to prepare biphasic HA/β-TCP and phase pure β-TCP.

Fig. 2 shows the XRD patterns of the calcium phosphate powders after ball milling for 12 h, from the precursor Ca/P ratios of 1.30, 1.50 and 1.67. A mixed phase of DCPD with HA phase was obtained with Ca/P ratio of 1.30. For the precursor Ca/P ratios of 1.50 and 1.67, the patterns are showing only the HA phase formed without other phases. There is no noticeable difference between the peaks for the precipitates prepared. In addition, the broad and weak intensity of the HA peaks indicates poor crystallinity and/or nanometer scale crystallites of the calcium phosphate powders prepared. The prepared powders are approximately 26 nm in particulate size for both cases calculated by the Scherrer's equation. The most distinct (002) reflections (near 2θ 26º) in the XRD patterns were taken into calculation.

Calcination temperature plays an important role in the phase formation, as shown in Fig. 3. In the case of Ca/P =1.30 powder, it showed that phase pure β-TCP was formed by consuming the pre-existing DCPD and HA as the calcination temperature increased from 500 ℃ to 900 ℃ (Fig. 3(a)). Biphasic calcium phosphate (β-TCP/HA) and single phase HA can be obtained from the powders with Ca/P ratios of 1.50 and 1.67, respectively. Fig. 3(b) shows that in the case of the powder from Ca/P = 1.50 the TCP phase appears with the pre-existing HA phase after calcination at 700 ℃ due to the phase transformation from amorphous to crystalline β-TCP. The β-TCP was the dominant phase thereafter. The percentage of volume fraction for β-TCP and HA was calculated using the relative intensity ratio (RIR) [14]. The HA/β-TCP ratio was estimated to be 35/65 at 900 ℃. For powders from the precursor Ca/P ratio of 1.67, the overall peaks of HA become more distinct with the increasing calcination temperature, and the narrow peak width suggests increased crystallinity and particulate size (Fig. 3(c)). The particulate size
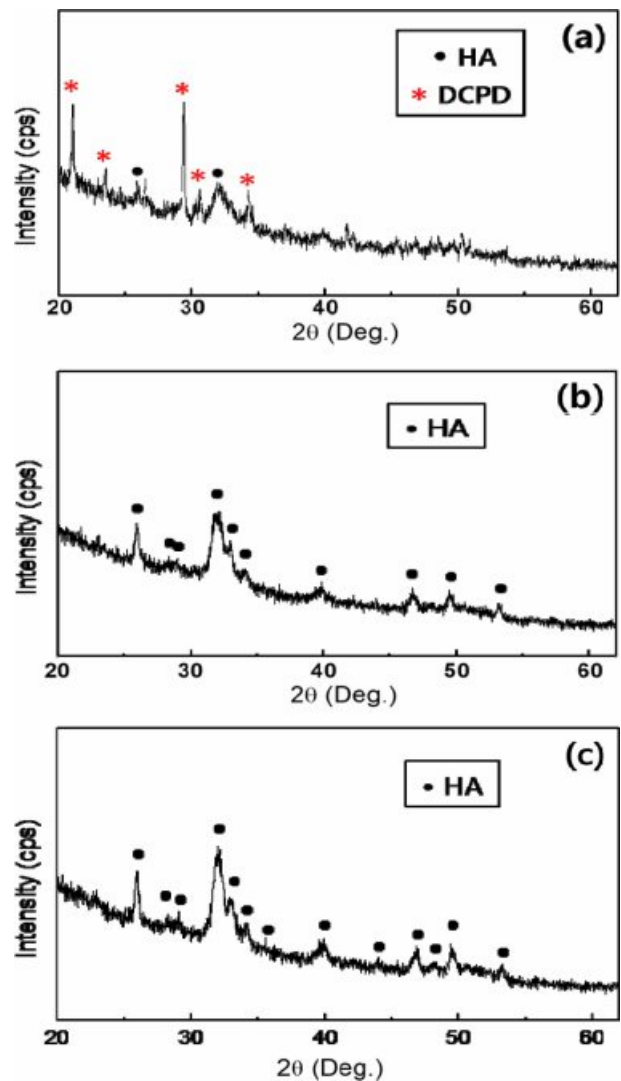

Fig. 2. XRD patterns of precipitated calcium phosphates powders from the different precursor Ca/P ratios: (a) Ca/P = 1.30, (b) Ca/P = 1.50, and (c) Ca/P = 1.67.

increased from 30 to 50 nm when the calcination temperature increased from 500 to 900 ℃, respectively. No impurity or secondary phases appeared in this case.

The sinterability of the synthesized powders is proportional to particle size. The ultra-fine particle size of as-prepared precipitates leads to higher sinterability. In this study, the diameter of the green pellets was 12.71 mm. After sintering at 1,100 ℃ for 2 h, the diameter has decreased to 9.85 mm (22.5% reduction for HA from Ca/P=1.67), 9.5 mm (25.3% reduction for β-TCP/HA from Ca/P=1.50) and 10.95 mm (18.5% reduction for β-TCP from Ca/P=1.30). The sintered bodies showed a certain degree of translucency showing good sinterability (Fig. 4). For pure HA, it is known that the sintering temperature to achieve such dense ceramics is 1,250 ℃ or higher [15, 16]. In particular, low temperature sintering is essential for β-TCP, because β-TCP reconstructively transforms into α-TCP above 1,125 ℃
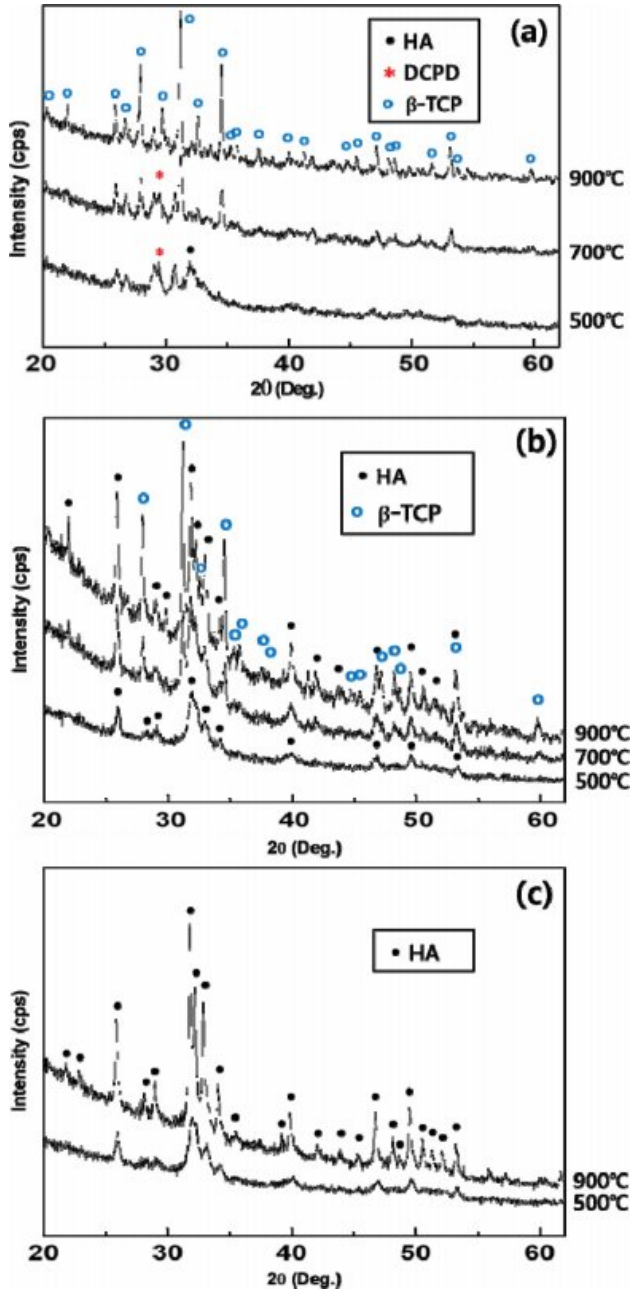
Fig. 3. XRD patterns of prepared calcium phosphates powders from the different precursor Ca/P ratios ((a) Ca/P = 1.30, (b) Ca/P = 1.50, and (c) Ca/P = 1.67) calcined at different temperatures.

Fig. 4. A translucency example for the sintered specimens at 1,100 ℃ for 2 h using the prepared calcium phosphates powders from the different precursor Ca/P ratios (TCP (Ca/P = 1.30), TCP/HA (Ca/P = 1.50), and HA (Ca/P = 1.67)).
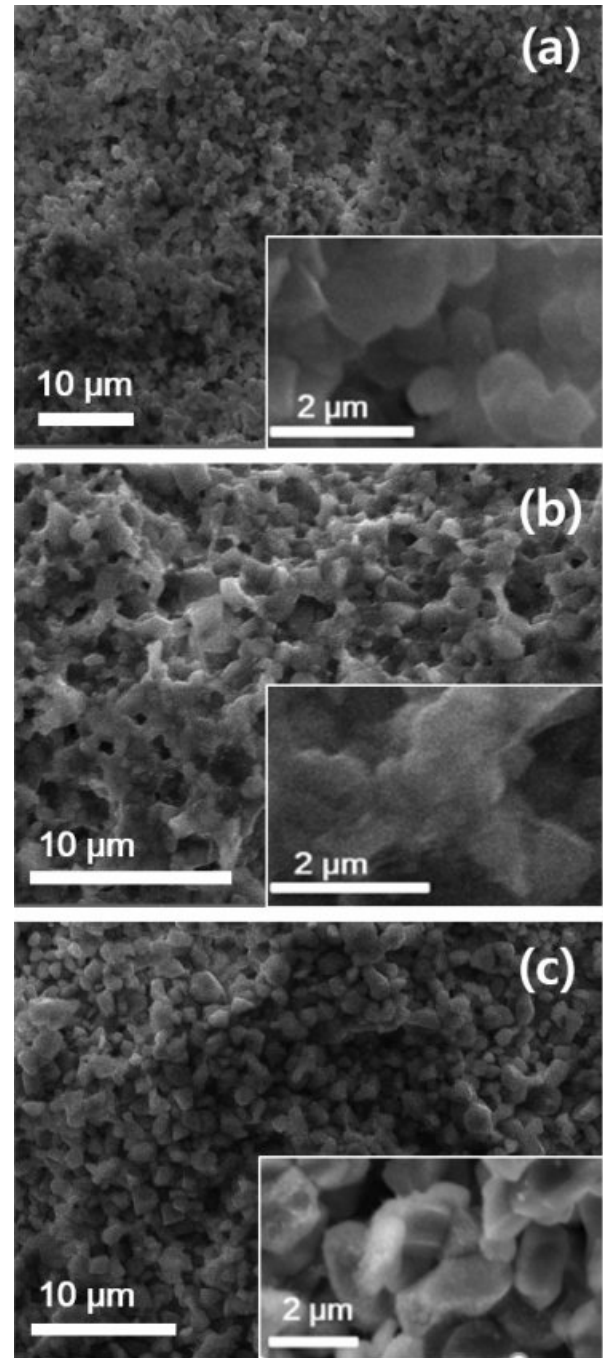

Fig. 5. SEM micrographs of the sintered ceramics at 1,100 ℃ for 2 h using the prepared powders from the different precursor Ca/P ratios: (a) TCP (Ca/P = 1.30), (b) β-TCP/HA (Ca/P = 1.50), and (c) HA (Ca/P = 1.67).

[17-19]. Ultrafine particles with high reactivity offered high-density ceramic products at the lower sintering temperature of 1,100 ℃. Fig. 5 shows the microstructures of sintered specimens with the precursor Ca/P ratios of 1.30, 1.50 and 1.67 at 1,100 ℃ for 2 h. Grains of around 0.5-1.8 μm in sizes are observed in the specimens.

In most chemical precipitation processes for calcium phosphates, the powder properties depend heavily on the processing parameters during the precipitation reaction due to the slow reaction rate and the unstable nature of the precursor solution. The morphology, phase, and crystallinity of precipitated powders were closely

related to precursor concentration, precursor dropping rate, reaction pH, and exposure (aging) time in solutions. For example, to prepare single HA phase particles, very slow precursor dropping rates such as a few drops per minute and a very long aging time over 24 h were essential at low aqueous precursor concentrations of less than 0.6 M Ca(OH)$_2$ [20, 21]. Furthermore, some wet chemical methods require an extra time-consuming washing step to rinse off by-products and excess reactants. However, in this study, nanometer scale HA, β-TCP, and biphasic β-TCP/HA powders were conveniently prepared in a fast and simple manner: about 100 times faster precursor dropping rate at higher precursor concentration without washing step. Therefore, it can be proposed that the modified process is economically feasible and capable of mass production in large quantities.

Conclusions

The modified approach of the aqueous precipitation method followed by the mechanical ball milling process offered a simple, convenient and economical route to synthesize calcium phosphates without the pH control and ripening time used in most wet precipitation studies. The ball milling step enhanced the reaction process and promoted the desirable phase synthesis in a short period of time. The biphasic HA/β-TCP composite and pure HA and β-TCP powders were synthesized according to the initial Ca/P ratio and heat treatment. It was shown that, as the heat treatment temperature increased, the phase pure β-TCP was formed by consuming the pre-existing DCPD and HA in the case of Ca/P = 1.30 powder. For Ca/P=1.50 powder, the biphasic HA/β-TCP was obtained, where the TCP phase appeared on the pre-existing HA phase after heat treatment at 700 ºC. Pure HA phase without any noticeable second phase can be synthesized without post heat treatment for the precursor Ca/P ratio of 1.67. Due to the high reactivity of the nanoparticles prepared via the modified route, highly dense ceramics with translucency were formed at a relatively low sintering temperature of 1,100 ºC.

Acknowledgments

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