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Substitution of dicarboxylate ions as succinate ion in ‘Apatite World’

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Abstract

In crystal chemistry, the apatite crystals is prepared by the dissolution precipitation reaction reaction, which led to HAP (hydroxyapatite; $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) nanocrystals formation under hydrothermal condition from OCP (octacalcium phosphate; $\text{Ca}_8(\text{HPO}_4)_2(\text{PO}_4)_4 \cdot 5\text{H}_2\text{O}$) at 180°C for 3 hours with adjusted 5.5 pH range. The prepared solution is incorporating to dicarboxylate as succinate ($\text{OOC}(\text{CH}_2)_2\text{COO}^{2-}$) ions. During incorporating of succinate ions in OCP crystals, the hydrogen phosphate (HPO_4^{2-}) ions in the hydrated layers of OCP are being substituted by succinate ions. These organically modified OCP which generated to HAP have unique hexagonal nanostructure with micrometer thickness are characterized by reporting of scanning electron microscopy (SEM), X-ray diffraction analysis, Fourier transform infrared (FTIR) spectra and Scherrer's equation as well.

Keywords: Succinate ion, octacalcium phosphate, hydroxyapatite, hydrogen phosphate, Scherrer's equation

1. Introduction

In chemistry of ‘apatite world’ the bio-apatite are indispensable for which the general formula is $\text{Ca}_5(\text{PO}_4)_3\text{X}$, where $\text{X}=\text{F}$, Cl or OH , since they are key component of bone and teeth. Recently, synthetic apatites that permit bone grafts are now available ^[1], but, a bone like nanocrystalline apatite have been formed *via* using self-assembled liquid crystals ^[2]. The hydroxyapatite (HAP; $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) which is the main inorganic components of hard tissue such as bone and teeth and they are used in medicinal application have attracted a great attention including several application such as artificial organs, tissue engineering, medical devices and dentistry etc ^[3]. Although, a NMR characteristic transformation behaviours of octacalcium phosphate (OCP; $\text{Ca}_8(\text{HPO}_4)_2(\text{PO}_4)_4 \cdot 5\text{H}_2\text{O}$) to HAP have been reported ^[4, 5], which is different from those of other calcium phosphate compounds under hydrothermal conditions (in *vitro-vivo*) ^[6-8]. The HAP can be synthesized from various calcium orthophosphates such as α - and β - tricalcium phosphate (TCP; $\text{Ca}_3(\text{PO}_4)_2$) and OCP as well ^[9]. For TCP, since HAP is generated by a dissolution precipitation reaction, there is no correlation between the crystal shape of the original TCP particle and the shape of the HAP particles generated. Generally, needle shaped HAP crystals are formed from granular α - and β -TCP particles under hydrothermal conditions ^[10, 11]. Plate-shaped OCP crystals are transformed to laminated thin plate- shaped HAP nanocrystals under hydrothermally and characterized the resultant HAP. The OCP crystal is composed of apatite and hydrated layers producing plate-shaped crystals ^[12, 13]. Where, the hydrogen phosphate ion (HPO_4^{2-}) in the hydrated layers can be substituted or incorporated by dicarboxylate such as succinate ions into OCP crystal structure has been reported ^[14-17]. The molecular structure of succinic acid and its ion is shown in figure 1.

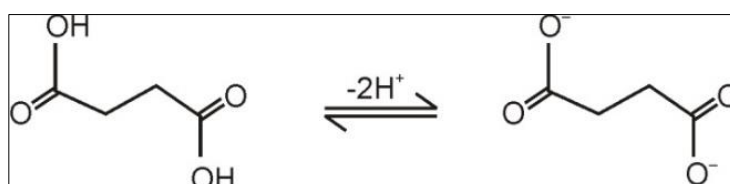


Fig 1: The molecular structure of succinic acid ($\text{HOOC}(\text{CH}_2)_2\text{COOH}$) and succinate ion ($\text{OOC}(\text{CH}_2)_2\text{COO}^{2-}$)

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2. Experimental

In experimental procedure, a dicarboxylic acid such as succinic acid based modified octacalcium phosphate (OCP; $\text{Ca}_8(\text{HPO}_4)_2(\text{PO}_4)_4 \cdot 5\text{H}_2\text{O}$) is incorporated with succinate ion has been synthesized by a previously reported method [18, 19]. Here, the our reported work is performed well by adapted from the work of as T. Yokoi *et al.* [20]. The required materials as chemicals and reagents have been laboratory-based standard is used. In this method, 20 mmol of succinic acid ($\text{HOOC}(\text{CH}_2)_2\text{COOH}$); 99.5%, (Wako Pure Chemical Industries Ltd., Osaka, Japan) is dissolved in 200 cm^3 of ultra-pure water, where the pH of solution is adjusted to 5.5 by adding an appropriate amount of ammonia solution (aqu. NH_3 soln.;25%). The 16.0 mmol of calcium carbonate (CaCO_3 ; calcite, Nacalai Tesque Inc., Kyoto, Japan) has been suspended in the dicarboxylic acid solution and 10.0 mmol of phosphoric acid (H_3PO_4 ; 85% aqu. soln, Wako Pure Chemical Industries Ltd) is mixed with the suspension. Then suspension is stirred at 60°C, after about 3h, the pH of the suspension is reduced to 5.0 by using 1.0 mol. dm^{-3} HCl solution and after 30 minutes, the precipitates has been isolated by vacuum filtration and gently rinsed with ultra pure water and ethanol ($\text{C}_2\text{H}_5\text{OH}$), followed by drying overnight at 40 °C.

The sample which synthesized in solution containing 20 mmol of succinic acid is denoted as Suc-20 as well as OCP those not containing dicarboxylate ion is also synthesized by using 16.0 mmol of CaCO_3 and 12.0 mmol of H_3PO_4 which may denoted as CONTROL or CALPHOS. Now, CALPHOS (0.10 g) and Suc-20(0.10 g) are added to a 28- cm^3 teflon vessel with 10 cm^3 of ultra pure water. The samples have encapsulated in an autoclave, and then hydrothermally treated at 180°C for 3h. These hydrothermal treatment condition under which the phase transformation is completed in a short time may selected because as the reaction time become longer, the morphological differences in the morphology of generated hexagonal HAP due to different starting materials disappear due to aging, where hydrothermally treated sample has collected by vacuum filtration and it dried overnight at 40°C, respectively.

The crystalline phases of the different hydroxyapatite (CALPHOS or CONTROL and Suc- or SUC 20) sample products have characterized by powder X-ray diffraction (XRD; RINT-2000, Rigaku Co., Tokyo, Japan) using $\text{Cu-K}\alpha$

radiation. The chemical structures of the given samples have characterized by using of Fourier- transform infrared (FTIR) spectroscopy (Frontier MIR/NIR, Perkin-Elmer Japan Co., Ltd., Kanagawa, Japan) as using the KBr tablet method. The morphologies of the formed samples have been characterized by scanning electron microscopy (SEM; SU-8000, Hitachi, Ltd., Tokyo, Japan) as well.

3. Results and Discussion

In this paper we have effort and try to mentioned that, about the succinate incorporated OCP, although, following a procedure well reported [18]. The report reveals that the Ca/P molar ratio of OCP with incorporated or complexed succinate (SUC- or Suc-OCP) ion is expected to be 1.56 ± 0.02 . The transformation of Suc-20 have proceeded under hydrothermal condition and Suc-OCP is completely transformed to HAP by hydrothermal treatment at 180°C for 3 hours. There is no by- products such as dicalcium phosphate anhydrous are detected by XRD analysis. It is reported that the colour of Suc-OCP changed from white to light brown upon heat treatment at 450°C in an air due to residual carbon formation. Notable, the colour of both CONTROL or CALPHOS and Suc-20 before and after hydrothermal treatment was white and non of the color may observed visually. Hence, succinate ion decomposition may not occur under the hydrothermal conditions. Here, in figure 2 (a and b) we have shown the XRD and SEM magnification image of OCP which are as starting materials for transformation reaction.

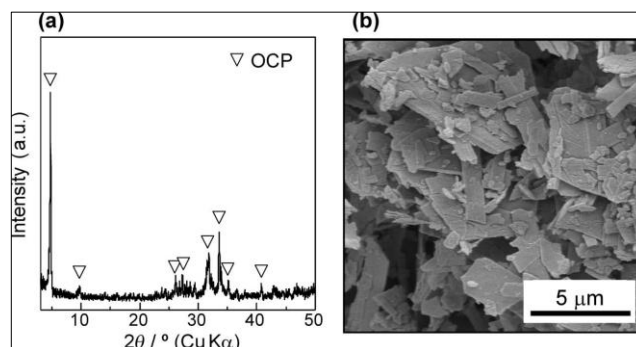


Fig 2: The XRD pattern (a), and (b) SEM image for OCP before hydrothermal treatment.

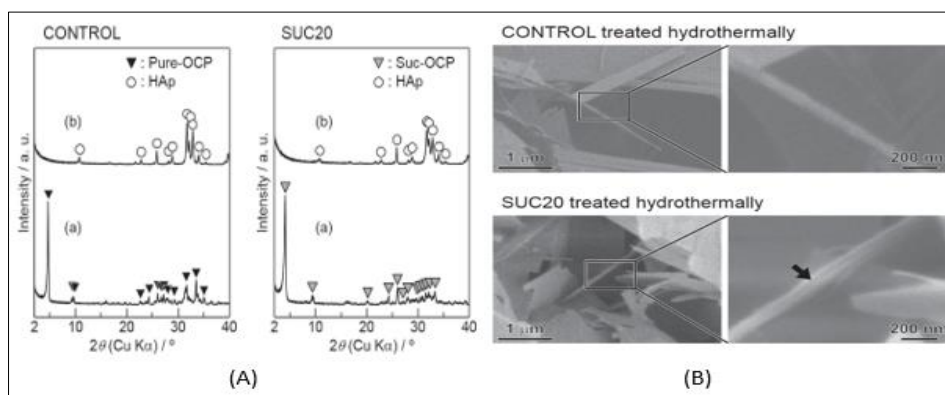
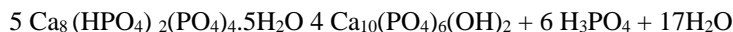


Fig 3: (A)- The XRD patterns of samples (CONTROL and SUC20) {under before (I), after (ii), and (B)- The SEM magnification images of sample under hydrothermally treatment at 180 °C for 3 hours, [20]

Indeed, the crystal morphology of the various samples (CALPHOS or CONTROL, Suc-20, Suc-OCP and Pure-OCP) before and after hydrothermal treatment at 180°C for 3

hours have been well assigned [19, 21]. Here, the figure 3 (A) has shown the crystalline phases of the different products are being characterized by powder X-ray diffraction (XRD),

and, in figure 3 (B) as scanning electron microscopy (SEM) observation of dark line at HAP crystal's center. The figure 4 (A) indicated FTIR spectra with the absorption peak of HPO_4^{2-} located in the hydrated layer is detected at 1193cm^{-1} , [22, 23]. This peak is not absorbed for Suc-20 because HPO_4^{2-} is replaced by the succinate ion. The observation peaks arising from the COO stretching and CH_2 bending modes of the complexed succinate ion are observed at 1565, 1460



In transformation reaction of OCP to HAP nanocrystals under hydrothermal condition as shown in equation 1, the pH of used solvent are 5.5 but its value may decrease in treatment conditions because the formation of phosphoric acid (H_3PO_4). In crystal morphology of the samples before and after hydrothermal treatment at 180°C for 3 hours have displayed that, both the as-synthesized and hydrothermally treated CALPHOS sample are composed of plate-shaped crystals several micrometers in size, although the crystalline phase is changed from OCP to hexagonal HAP. Therefore, for pure-OCP, the crystal morphology is almost retained after phase transformation [12, 13]. Similarly, to CALPHOS

and 1300cm^{-1} . After the hydrothermal treatment, the absorption peak corresponding to HAP are detected for both hydrothermally treated CALPHOS and Suc-20. Although, in some cases, hydrothermally synthesized HAP includes carbonate ions in its crystal lattice, the absorption peaks corresponding to the carbonate ion are not detected in our samples. In respect of crystalline phase the FTIR spectral observation are in line with XRD results.

there is no change in the macroscopic morphology for Suc-20. These finding strongly suggested that the phase transformation mechanism for Suc-OCP is similar to that of pure-OCP. On the basis of SEM images report of the different samples we observed that, the HAP crystals, where the thickness of HAP crystals, formed by the hydrothermal treatment of CALPHOS is in range 50-150nm similar to those of plate-shaped crystals before hydrothermal treatment. The present observation have shown the dark line are found at the centre of the Suc-20 crystal after hydrothermal treatment, which can attributed to the gap between two thin-plate crystals.

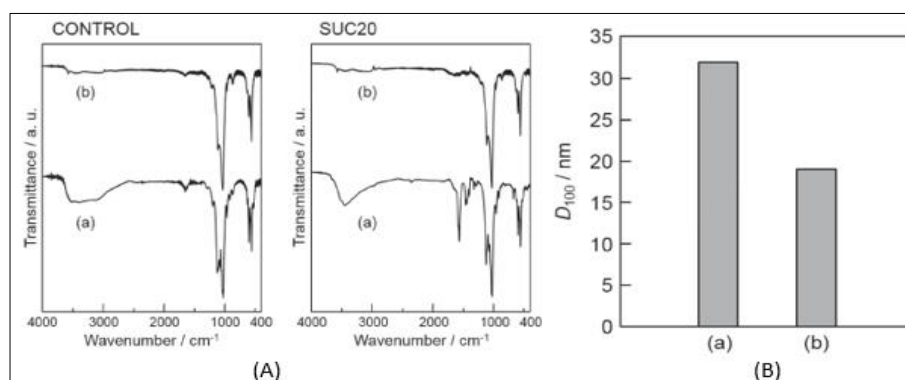


Fig 4: (A)- The FTIR spectra of samples CONTROL and SUC20 under before (a), and after (b) hydrothermal treatment at 180°C for 3 hours, and (B)- The D_{100} values of hydroxyapatite (HAP) prepared from, (a) CALPHOS and (b) Suc-20, calculated by using of Scherrer equation, [20].

Although, a survey reveals that the crystalline system for HAP is hexagonal, where the crystallite size in the direction of the various axes (a,b,c) dependent on the thickness of the plate-shaped HAP crystals [13, 20, 24, 25]. These crystallite size perpendicular to the (100) plane which are calculated by the using of Scherrer equation (as equation 2) to compare the thickness of the plate-shaped HAP crystal of CALPHOS and Suc-20 after hydrothermal treatment at 180°C for 3 hours.

$$D_{100} = K \lambda / (\beta \cos\theta) \quad [2]$$

Here, the D_{100} is the crystallite size perpendicular to (100) plane, K is Scherrer constant ($=0.9$), λ is the wavelength of incident X-ray (0.154 nm), β is the full width at half-maximum of the 100-reflection peak for HAP and θ is the diffraction angle. Figure 4 (B) show that the D_{100} values of samples as HAP synthesized from Suc-20 are smaller than those of HAP prepared from CALPHOS. Thus, calculation of crystallite size support as well as SEM agreement that, the presence of dark line corresponding to gap between to thin-plate crystals, therefore, the HAP crystal which are obtained from Suc-20 likely have laminated nanostructures. Where, the elimination of succinate ion from interlayer of OCP crystal is necessary for the transformation from OCP

with incorporated succinate ion to HAP. The laminated nanostructure is formed probably because the succinate ions inhibit crystal growth in the thickness direction.

4. Conclusion

In conclusion, we have reported the study of preparation and characterization of a hydroxyapatite (HAP) nanocrystals *via* hydrogen phosphate (HPO_4^{2-}) ions substitution in hydrated layers of octacalcium phosphate (OCP) by dicarboxylate as succinate ions ($\text{OOC}\cdot\text{CH}_2\text{-CH}_2\cdot\text{COO}$)²⁻. These crystals are transformed through hydrothermal precipitation reaction at 180°C for 3 hours with adjusted pH to 5.5 and incorporated to dicarboxylic (e.g. succinic) acid having Ca/P molar ratio expected to be 1.56 ± 0.02 . During incorporation of organically succinate ions into OCP crystal, the substitution of hydrogen phosphate (HPO_4^{2-}) ions in hydrated layer of OCP are replaced by succinate ions. The crystalline size and thickness of generated hexagonally plate-shaped HAP are calculated by introducing of Scherrer's equation. The characteristic observation of produced hexagonally HAP nanocrystals have been studied by using of SEM, Fourier Transform Infrared (FTIR) and powder XRD technique as well.

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