J Mater Sci: Mater Med (2008) 19:1183–1186
DOI 10.1007/s10856-007-3209-0

Variation of crystal structure of hydroxyapatite in calcium phosphate cement by the substitution of strontium ions

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Received: 18 December 2006 / Accepted: 6 June 2007 / Published online: 15 August 2007

Abstract New routes were used to introduce strontium into calcium phosphate cement in the present article. The study showed that by mixing 50 wt% amorphous calcium phosphate + amorphous strontium phosphate and 50 wt% dicalcium phosphate dihydrate, hydroxyapatite and Sr-hydroxyapatite precipitated separately in the hydrated cement; whereas, by mixing 50 wt% Sr- amorphous calcium phosphate and 50 wt% dicalcium phosphate dihydrate, strontium can be doped into hydroxyapatite lattice and increase the lattice dimensions and lattice volume. The strontium substituted calcium phosphate cement has potential for use in orthopedic surgeries.

Introduction

Calcium phosphate cements (CPCs) have been developed since 1983 [1]. They are suitable for the repair and reconstruction of bone [2–4]. Because they are osteotransductive, after implantation in bone defects they are rapidly integrated into the bone structure. Calcium phosphate cements are composed of one or more calcium phosphates that, once mixed with a liquid phase, give a moldable paste. Within a few minutes, the paste sets because of the in situ formation of a solid calcium phosphate. The setting reaction provokes hardening of the paste through entanglements of the crystals of the precipitate [5].

Ionic strontium shares the same physiological pathway as calcium and can be deposited into the mineral structure of the bone, especially into the regions of high metabolic turn-over [6]. As a trace element in bone, strontium has been reported to exert a beneficial effect on osteoblastic activity [6–10]. Thus, its incorporation into calcium phosphate cements has been the subject of much interest in the last decade [6–10]. In vivo (Ca, Sr)HA cement study revealed an increase in the thickness of the bone layer formed at the bone-cement interface and better osteointegration, as compared to pure CaHA [7]. Moreover, strontium substituted HA can lead to a slight shift to lower 2θ angles of the diffraction peaks of the apatite phase [8].

In previous works, Sr-containing CPCs have been prepared by using Sr-substituted α-TCP [8], strontium hydrogen phosphate [9] and strontium nitrate [10]. In the present paper, new routes were used to introduce strontium into CPC and the phase composition was presented.

Experimental

Material preparation

Route 1: The strontium-containing hydroxyapatite (Sr-HA) bone cement with a Sr/(Sr + Ca) molar ratio of 0%, 2.5%, 5%, 7.5% and 10% was prepared as the mixture of 50 wt% amorphous calcium phosphate (ACP) + amorphous strontium phosphate (ASP) and 50 wt% dicalcium phosphate dihydrate (DCPD).

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Route 2: The strontium-containing hydroxyapatite (Sr-HA) bone cement with a Sr/(Sr + Ca) molar ratio of 0%, 2.5%, 5%, 7.5% and 10% was prepared as the mixture of 50 wt% strontium-containing ACP (Sr-ACP, with a Sr/(Sr + Ca) molar ratio of 0%, 5%, 10%, 15% and 20%) and 50 wt% DCPD.

ACP, ASP and Sr-ACP was synthesized from an aqueous solution of $Ca(NO_3)_2 \cdot 4H_2O + (NH_4)_2HPO_4 \cdot 12H_2O$, $Sr(NO_3)_2 + (NH_4)_2HPO_4 \cdot 12H_2O$ and $Ca(NO_3)_2 \cdot 4H_2O + Sr(NO_3)_2 + (NH_4)_2HPO_4 \cdot 12H_2O$ by chemical precipitation method in our laboratory, respectively. Then the deposit was centrifugally separated and freeze-dried. DCPD was commercially obtained form the Shanghai No. 4 Reagent & H.V. Chemical Co. Ltd, China. The CPC powders were homogeneously mixed with de-ionized water for 1 min. In this study, the liquid to powder ratio was fixed to 0.4 mL/g. And the tests were done at 25 °C for all experiments.

Phase and microstructure characterization

The hydrated samples were milled into powder and analyzed using XRD (X'Pert Pro, PANalytical Co., the Netherlands) using CoKα radiation and FTIR (AVATAR 360, Nicolet Co., USA).

Results and discussion

Figure 1 shows the XRD patterns of the hydrated CPC with different content of strontium introduced by "Route 1". For the cement without strontium, only characteristic peaks of HA (JCPDS card 01-074-0566) appeared in the XRD pattern. With the introduction of strontium, characteristic peaks of Sr-HA (JCPDS card 01-070-1511) appeared besides HA's peaks. This meant that strontium didn't substitute into the HA lattice. With the increase in the relative amount of strontium, the characteristic peaks of Sr-HA became narrow and intense.

Figure 2 shows the XRD patterns of the hydrated CPC with different content of strontium introduced via "Route 2". When the relative amount of strontium increased from 0% to 10%, only characteristic peaks of HA appeared in the XRD patterns. The diffraction patterns of the CPC powders were slightly and continuously shifted to lower diffraction angles as increasing Sr amounts were introduced, indicating that the changes in lattice parameters happened due to the substitution of Sr for Ca in HA lattice.

Figures 3 and 4 show the variation of the lattice dimensions and lattice volume of (Ca, Sr)HA with increasing Sr content introduced by "Route 2". Rietveld refinement analyses performed on the powder data revealed an almost linear evolution of the lattice parameters. With the increase in the relative amount of strontium, the lattice dimensions and lattice volume of (Ca, Sr)HA increased (a, b from 9.4151 Å to 9.5383 Å, c from 6.8794 Å to 6.9556 Å, V from 528.11 $Å^3$ to 548.03 $Å^3$). Ishikawa and his co-workers [11] suggested that the lattice parameters of the a- and c-axes of the apatite structure elongated with the increase in Sr content. The increase in the lattice dimensions and lattice volume indicates that strontium is incorporated in the HA structure (ionic radii: Sr^{2+} = 1.13 Å, Ca^{2+} = 1.00 Å) [12].

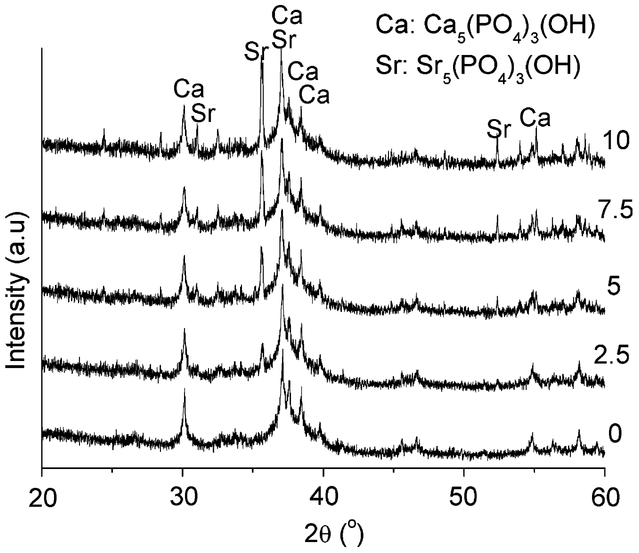

Fig. 1 XRD patterns of the hydrated CPC with different content of strontium introduced by "Route 1". 0, 2.5, 5, 7.5, 10 meant the Sr/(Sr + Ca) molar ratio of 0%, 2.5%, 5%, 7.5% and 10%, respectively

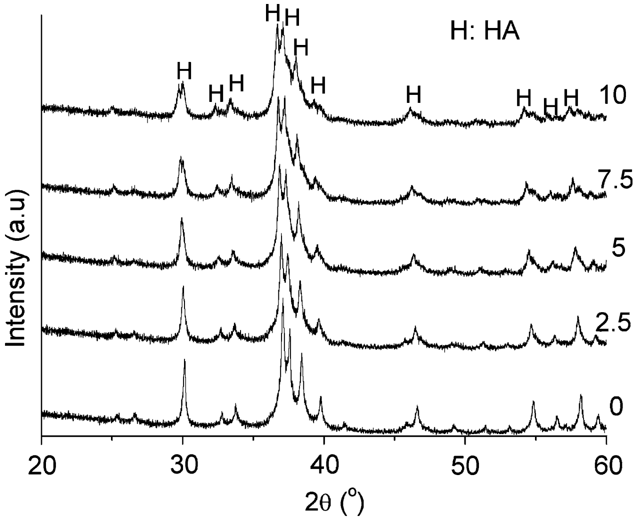

Fig. 2 XRD patterns of the hydrated CPC with different content of strontium introduced by "Route 2". 0, 2.5, 5, 7.5, 10 meant the Sr/(Sr + Ca) molar ratio of 0%, 2.5%, 5%, 7.5% and10%, respectively

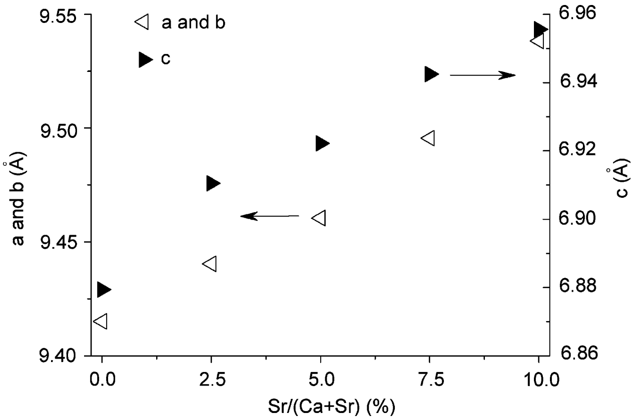

Fig. 3 Variation of the lattice dimensions of (Ca, Sr)HA with increasing Sr content introduced by "Route 2"

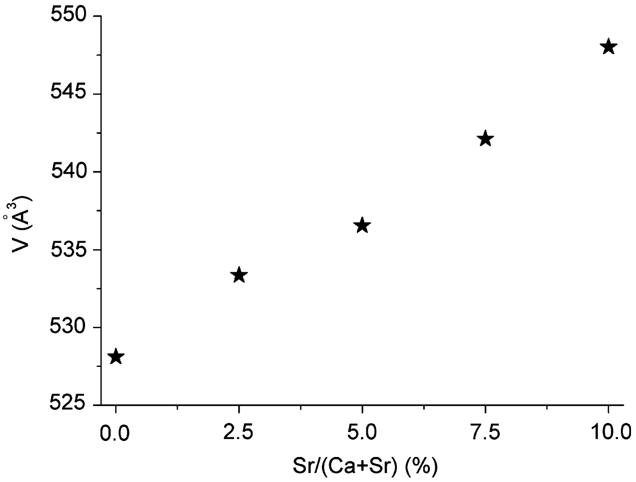

Fig. 4 Variation of the lattice volume of (Ca, Sr)HA with increasing Sr content introduced by "Route 2"

Figure 5 shows the FTIR spectra of the hydrated CPC with different content of strontium introduced by "Route 2". With the increase in the relative amount of strontium, the PO_4^{3-} bands appeared in the follow range: 1090–1030 cm^{-1}, 957 cm^{-1}, and 600–500 cm^{-1} were slightly and continuously shifted to lower wavenumbers. This is in accordance with the result reported by Kano et al. [13]. This also proves that strontium has been incorporated in the HA lattice. The results from the XRD analysis and the FTIR analysis were consistent.

In "Route 1" during the preparation of the cement, the calcium and strontium ions containing powders ACP and ASP were physically mixed together. Thus it was hard for the strontium to substituted into the lattice of HA. In "Route 2" during the synthesis of Sr-ACP, the calcium and strontium ions were chemically homogeneously mixed together in solution. This was in favor of the strontium substituting into the lattice of HA.

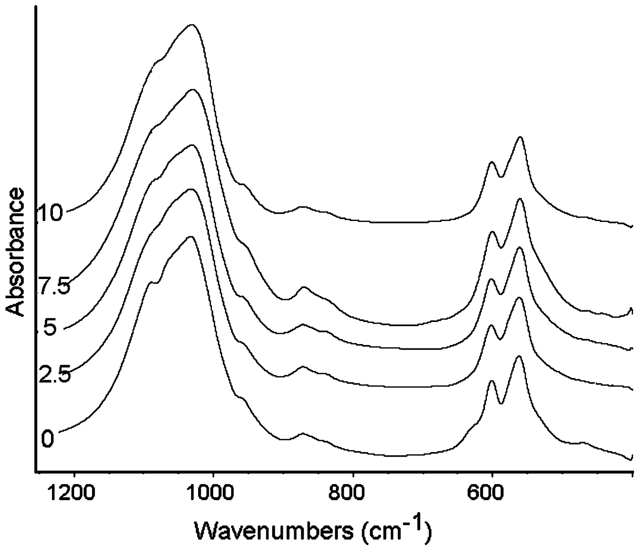

Fig. 5 FTIR spectra of the hydrated CPC with different content of strontium introduced by "Route 2". 0, 2.5, 5, 7.5, 10 meant the Sr/(Sr + Ca) molar ratio of 0%, 2.5%, 5%, 7.5% and 10%, respectively

Conclusions

In the present article, new routes were used to introduce 0–10% strontium into calcium phosphate cement. The results showed that by mixing 50 wt% ACP + ASP and 50 wt% DCPD, HA and Sr-HA precipitated separately in the hydrated cement. Whereas, by mixing 50 wt% Sr-ACP and 50 wt% DCPD, strontium substituting into the HA lattice and increased the lattice dimensions and lattice volume. The strontium substituted CPC cement has potential for use in orthopedic surgeries.

Acknowledgements The authors are grateful to the National Natural Science Foundation of China under Grant 50172015 and the Science and Technology Program of Guangzhou under Grant 2005Z3-D2041.

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