

Barium Calcium Hydroxyapatite Solid Solutions

Adriana Bigi,* Elisabetta Foresti, Fulvia Marchetti, Alberto Ripamonti, and Norberto Roveri

Istituto Chimico 'G. Ciamician' dell'Università di Bologna, via F. Selmi 2, 40126 Bologna, Italy

The replacement of calcium by barium in the hydroxyapatite structure by solid-state reaction at different temperatures and by precipitation from an aqueous system has been investigated by X-ray diffraction and i.r. absorption analyses. The products obtained by solid-state reaction at 1 200 °C are solid solutions over the range of barium concentration 60–100 atom %. The lattice dimensions and the i.r. frequencies of the solid solutions vary linearly with the atom % of barium. Only small amounts of barium can be incorporated in hydroxyapatite by precipitation from the aqueous system.

Biological as well as mineral apatites can be assumed to be calcium apatites associated with many other elements in both small and large amounts.^{1–5} The incorporation of substituents in synthetic apatites often depends on apatite preparation; remarkable differences have been observed between apatites prepared from aqueous and those prepared from non-aqueous systems.⁶

Substitution of various cations for calcium in the calcium apatite are accompanied by changes in the apatite lattice parameters and these changes are related to the size of the ionic radius of the cation compared to that of calcium.

Magnesium cannot substitute for calcium in the hydroxyapatite structure and, in aqueous systems, it promotes the formation of tricalcium phosphate at the expense of apatite.^{7,8}

Calcium strontium fluoroapatites and hydroxyapatites and strontium barium fluoroapatites form continuous series of solid solutions.^{9–12} Calcium barium fluoroapatites have a zone of immiscibility,¹³ whereas the calcium barium hydroxyapatite system obtained from aqueous solution has been studied only over a limited range of concentration.¹⁴

The aim of this work is to investigate the range of barium atom concentration in which barium and calcium hydroxyapatites form solid solutions from aqueous and non-aqueous systems and to determine the dependence of the lattice parameters on barium atom concentration.

Experimental

Calcium hydroxyapatite was prepared by neutralization of a Ca(OH)₂ solution with H₃PO₄ with stirring at 37 °C. The product was stored for 1 week in contact with the mother solution, then filtered off, washed with distilled water and dried at 100 °C. The products were heat treated at 1 000 °C for 15 h to eliminate any CO₃²⁻ present.

Synthetic barium hydroxyapatite was prepared by heating Ba(OH)₂ and (NH₄)₂HPO₄ together in a molar ratio of 1.67 : 1. After heating at 700 °C for 15 h, the material was mixed and reheated at 1 000 °C for 15 h.

Barium calcium hydroxyapatites were prepared following two different methods.

Method A. Mixtures of calcium hydroxyapatite and barium hydroxyapatite with barium ranging from 0 to 100 atom % were heat treated at different temperatures up to 1 200 °C. Every heat treatment was carried out for 15 h.

Method B. A solution of calcium and barium acetate was added dropwise to a stirring sodium monohydrogenphosphate solution maintained at 100 °C for 5 h. The barium concentration in the solution was in the range 0–100 atom %. The total cation concentration in the acetate solution was 0.005 mol dm⁻³ while the phosphate solution concentration was 0.003 mol dm⁻³. The precipitate was stored in contact with

the mother solution overnight, then filtered off, washed with distilled water, and dried at 100 °C.

X-Ray diffraction analysis was carried out using a Philips powder diffractometer with Ni-filtered Cu-K radiation. The lattice constants were determined from diffractometer data. The 2θ diffraction range covered was 10–65° at a scanning speed of 0.5° min⁻¹.

For i.r. absorption analysis, ca. 1 mg of the powdered samples was mixed intimately with 300 mg of KBr (i.r. grade) and pelleted under vacuum. The pellets were analysed using a Perkin-Elmer 390 IR grating spectrophotometer, range 4 000–400 cm⁻¹, normal slit, and scanning speed of 72 cm⁻¹ min⁻¹.

Barium content was determined using an atomic absorption spectrophotometer (Perkin-Elmer 373).

Results

The X-ray diffraction patterns of calcium hydroxyapatite, Ca₅(OH)(PO₄)₃, and barium hydroxyapatite, Ba₅(OH)(PO₄)₃, after heat treatment at 1 000 °C, show a high degree of crystallinity of both synthetic apatites. The lattice parameters determined by X-ray diffraction maxima are as given below.

$$\text{Ba}_5(\text{OH})(\text{PO}_4)_3 : a = 1.0191(3), c = 0.7747(3) \text{ nm}$$

$$\text{Ca}_5(\text{OH})(\text{PO}_4)_3 : a = 0.9413(1), c = 0.6872(1) \text{ nm}$$

The i.r. absorption spectra of Ca₅(OH)(PO₄)₃ and Ba₅(OH)(PO₄)₃ after heat treatment at 1 000 °C show no appreciable differences from those reported by Fowler¹⁵ for the products prepared by a hydrothermal method similar to those used by Klement¹⁶ and Klement and Dihn.¹⁷

The i.r. spectra of Ca₅(OH)(PO₄)₃ heat treated at temperatures less than 1 000 °C show absorption bands characteristic of CO₃²⁻. These bands are no longer present in the spectrum recorded after heat treatment of the apatite at 1 000 °C.

Mechanical mixtures of calcium hydroxyapatite and barium hydroxyapatite with barium atom % ranging from 0 to 100 have been prepared. The X-ray diffraction analysis reveals that solid-state reactions of these mixtures at 1 200 °C form solid solutions only in the range of barium atom concentration 60–100%. Hydroxyapatite, β-tricalcium phosphate, and barium-substituted tricalcium phosphate are the crystalline products obtained by heat treatment at 1 200 °C of the mixtures containing 0–60 barium atom %.

The Ca₅(OH)(PO₄)₃ and Ba₅(OH)(PO₄)₃ mixtures with 60–100 atom % barium heat treated at different temperatures ranging from 700 to 1 200 °C allow the formation of the solid solutions to be followed. The X-ray diffraction maxima of Ba₅(OH)(PO₄)₃ present in the patterns of these mixtures treated up to 900 °C do not change appreciably with respect

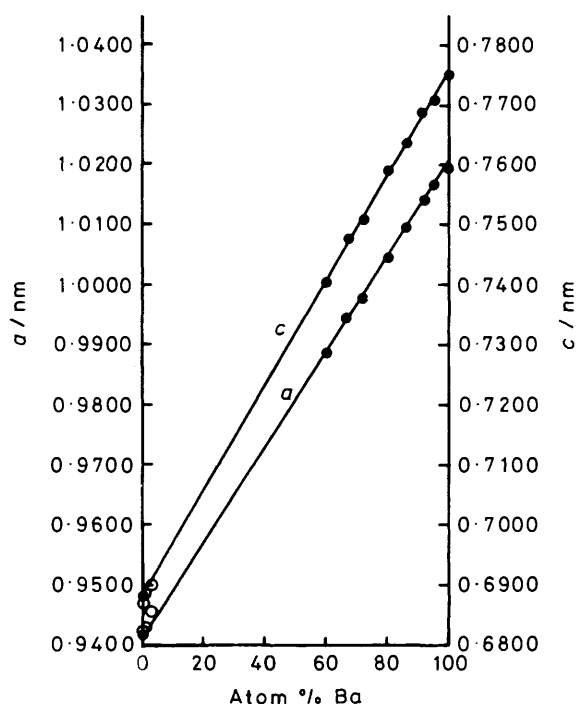


Figure 1. Plot of lattice constants of calcium barium hydroxyapatite solid solutions against atom % of barium: data for solid solutions obtained from method A (●) and from method B (○)

to those of pure $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$. After heat treatment at higher temperatures a shoulder at higher values of 2θ appears associated with every $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$ diffraction maximum. These shoulders become more and more sharp and identifiable as the diffraction maxima of calcium-substituted $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$, while the diffraction maxima of $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$ reduce in intensity until they disappear as the heat treatment temperature increases.

The cell parameters a and c of the apatitic phase obtained by solid-state reaction at 1200°C are plotted in Figure 1 against barium concentration. The parameters vary linearly with the composition, within experimental error, according to the following equations obtained by least-squares fit; x

$$a = (0.9412 + 0.000789x) \text{ nm, with } \sigma(a) = 2.5 \times 10^{-4} \text{ nm}$$

$$c = (0.6883 + 0.000872x) \text{ nm, with } \sigma(c) = 2.5 \times 10^{-4} \text{ nm}$$

is the barium concentration expressed as barium atom % and σ values are the standard deviations. The c/a ratio and the cell volume (V) vary with the composition according to the equations below; these are consistent with the linear behaviour of the cell parameters.

$$c/a = 0.07313 + 0.0000291x, \text{ with } \sigma(c/a) = 3.13 \times 10^{-5}$$

$$V = (52.69 + 0.170x) \text{ nm}^3, \text{ with } \sigma(V) = 0.03 \text{ nm}^3$$

The i.r. frequencies of the PO_4^{3-} and OH^- internal modes of the different solutions, plotted against the barium atom concentration in Figure 2, reveal that the frequencies of the vibrational modes of barium hydroxyapatite shift towards the frequencies of the corresponding vibrational modes of calcium hydroxyapatite as the barium atom concentration of the solid solution decreases. Except for the frequency of the OH^- stretching mode, which increases with increase of barium atom concentration, all the other i.r. frequencies de-

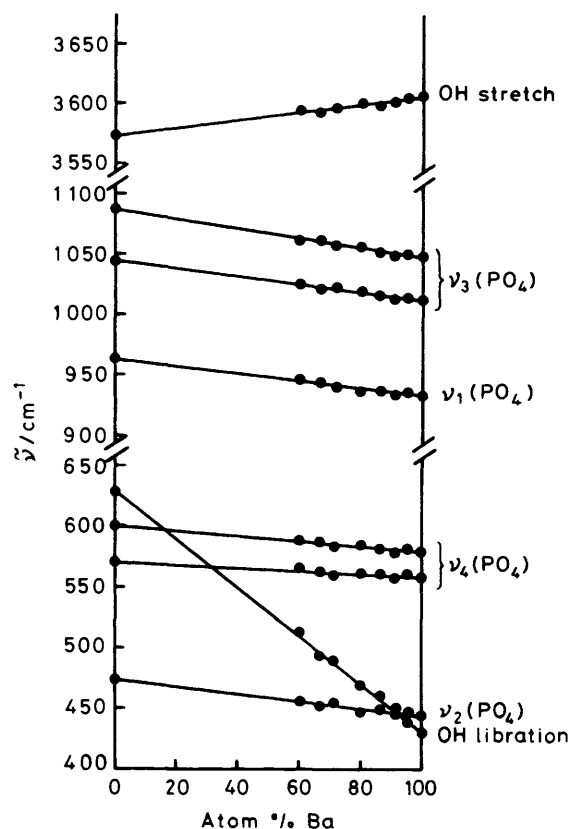


Figure 2. Infrared frequencies of the vibrational modes of calcium barium hydroxyapatite solid solutions against atom % of barium

crease nearly linearly with increasing barium content. Furthermore, the i.r. absorption spectra show that the band areas of the hydroxyl modes decrease as the barium atom concentration increases.

At variance to the behaviour of the products obtained from the $\text{Ca}_5(\text{OH})(\text{PO}_4)_3$ and $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$ mixtures, the precipitates obtained at 100°C by dropwise addition of calcium and barium acetate solutions into a stirring phosphate solution are constituted by solid solutions only in the range of barium concentration in solution from 0 to 25 atom %. Amorphous precipitates were obtained from solutions containing a barium concentration of 25–60 atom %. At higher barium concentration, tribarium phosphate was obtained.

The apatitic phase obtained in the range of barium concentration 0–25 atom % has been recognised by X-ray diffraction analysis as calcium hydroxyapatite with expanded cell parameters. The cell parameters and the barium content (expressed as barium atom %) of the samples obtained from solutions with barium concentration up to 10 atom % and heat treated at 100°C are reported in the Table. The cell parameters of the samples obtained from solutions containing a barium concentration >10 atom % are not reported since their measurement is difficult. In fact, on increasing barium concentration a broadening of the X-ray diffraction maxima and a reduction in their intensity have been observed. The variation of the cell parameters as a function of barium content follows a linear relationship very close to that found for the products prepared using Method A, as can be seen in Figure 1.

No attempt to correlate the i.r. frequencies of PO_4^{3-} and OH^- with barium atom concentration of the products obtained from aqueous solutions was made because the bands

Table. Unit-cell parameters of barium calcium hydroxyapatites obtained from method B, with estimated standard deviations in parentheses

Atom % Ba in solution	Atom % Ba in the solid phase	<i>a</i> axis (nm)	<i>c</i> axis (nm)
0	0	0.9427(2)	0.6875(3)
5	1.9(1)	0.9432(3)	0.6886(3)
10	2.8(1)	0.9461(4)	0.6901(4)

are broader than those of the samples obtained from Method A and the frequency variations are slight in the explored range of concentration.

It should be noted that the apatitic precipitates from aqueous solutions after heat treatment at 1 200 °C reveal a complete conversion into a crystalline phase corresponding to α -tricalcium phosphate.

Discussion

We have investigated by *X*-ray diffraction and i.r. absorption analyses the replacement of calcium by barium in the hydroxyapatite structure prepared by solid-state reaction at different temperatures and by precipitation from aqueous systems. The results of the *X*-ray diffraction analysis carried out on the products obtained by solid-state reaction of $\text{Ca}_5(\text{OH})(\text{PO}_4)_3$ and $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$ mixtures with 60–100 atom % barium show the formation of calcium-substituted barium hydroxyapatite just after heat treatment at temperatures above 900 °C. This phase is a solid solution which exhibits lattice parameters which vary linearly with the barium atom concentration. Furthermore, in spite of the presence of a zone of immiscibility, the *a*- and *c*-axis dimensions expand according to the law of Vegard. The cell volume increases with the barium atom % as expected because of the larger size of the barium ion compared with calcium. On heating up to 1 200 °C $\text{Ca}_5(\text{OH})(\text{PO}_4)_3$ and $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$ mixtures containing 0–60 barium atom %, products are formed containing different amounts of calcium hydroxyapatite, β -tricalcium phosphate, and barium-substituted tricalcium phosphate depending on the composition of the reaction mixture.

The frequencies of the vibrational modes of calcium barium hydroxyapatite solid solutions assume values lying on the straight line joining the characteristic frequencies of pure calcium and barium hydroxyapatites. The decrease of the magnitude of the OH bands with the increase of barium atom concentration is in agreement with the results obtained on calcium, strontium, and barium apatites by Fowler¹⁵ who attributed the differences in OH band intensity to differences in OH bonding.

Barium-substituted calcium hydroxyapatite has been prepared also by reaction of calcium and barium acetates with aqueous phosphate solution in the barium concentration range 0 to ca. 25 atom %. An expansion of the *a*- and *c*-axis dimensions, which follow the same law observed for solid solutions prepared by solid reaction, has been observed by increasing the barium concentration in solution up to 10 atom

%. Similar increase of the lattice parameters has been observed by Le Geros *et al.*¹⁴ for barium calcium hydroxyapatites obtained from aqueous solutions containing 5 and 10 atom % of barium. However, a comparison with our data is not possible because Le Geros *et al.* did not indicate the amount of barium incorporated from aqueous solution. In fact, our analytical data show that the concentration of barium in the solid solution is always less than the concentration in aqueous solution, as is shown in the Table. A further barium incorporation in the calcium hydroxyapatite produces a broadening in the *X*-ray diffraction peaks and a reduction in the intensity of these peaks. These effects, which indicate a reduction in crystallite size and/or an increase of the disorder of the crystal, are accompanied by a thermal instability of the apatite phase, which is transformed in α -tricalcium phosphate on heating at 1 200 °C.

In conclusion, homogeneous solid solutions cannot be formed in all proportions between $\text{Ca}_5(\text{OH})(\text{PO}_4)_3$ and $\text{Ba}_5(\text{OH})(\text{PO}_4)_3$, similarly to that observed for the calcium barium fluoroapatite system, which shows a zone of immiscibility between 6 and 64 atom % of barium.¹³ However, a large substitution of barium for calcium in the hydroxyapatite structure has been obtained only by solid-state reaction, while small amounts of barium can be incorporated in $\text{Ca}_5(\text{OH})(\text{PO}_4)_3$ by precipitation from an aqueous system.

Acknowledgements

We are grateful to the C.N.R., Italy, for financial support.

References

- 1 D. McConnel, *Arch. Oral Biol.*, 1965, **10**, 421.
- 2 W. D. Armstrong and L. Singer, *Clin. Orthopaed.*, 1965, **38**, 179.
- 3 D. McConnel, 'Apatites. Applied Mineralogy,' Springer, New York and Vienna, 1963, vol. 5.
- 4 R. W. Mooney and M. A. Aia, *Chem. Rev.*, 1961, **61**, 433.
- 5 W. A. Deer, R. A. Howie, and J. Zussman, 'Rock Forming Minerals, Non-silicates,' Wiley, New York, 1963, vol. 5, pp. 323–339.
- 6 R. Z. Le Geros, 1st International Congress on Phosphorus Compounds, Rabat, October 17–21, 1977, p. 347.
- 7 R. Z. Le Geros, W. P. Shirra, M. A. Miravite, and J. P. Le Geros, *Colloq. Int. C.N.R.S.*, 1975, **230**, 105.
- 8 A. Bigi, E. Foresti, F. Marchetti, A. Ripamonti, and N. Roveri, *J. Inorg. Biochem.*, 1981, **15**, 317.
- 9 R. L. Collin, *J. Am. Chem. Soc.*, 1959, **81**, 5275.
- 10 E. Hayek and H. Petter, *Monatsh. Chem.*, 1960, **91**, 356.
- 11 H. M. Heijligers, F. C. M. Driessens, and R. M. H. Verbeck, *Calif. Tissue Int.*, 1979, **29**, 127.
- 12 A. N. Akhavan-Niaki and R. Wallaey, *C.R. Hebd. Seances Acad. Sci.*, 1958, **246**, 1056.
- 13 A. N. Akhavan-Niaki and G. Montel, *C.R. Hebd. Seances Acad. Sci.*, 1959, **248**, 2486.
- 14 R. Z. Le Geros, M. H. Taheri, G. B. Quirolgico, and J. P. Le Geros, Proceedings of 2nd International Congress on Phosphorus Compounds, Boston, April 1980, p. 89.
- 15 B. O. Fowler, *Inorg. Chem.*, 1974, **13**, 207.
- 16 R. Klement, *Z. Anorg. Allg. Chem.*, 1939, **242**, 215.
- 17 R. Klement and P. Dihn, *Z. Anorg. Allg. Chem.*, 1938, **240**, 31.

Received 14th March 1983; Paper 3/395