Structural Modifications of Hydroxyapatite induced by Lead Substitution for Calcium

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Continuous series of solid solutions of lead and calcium hydroxyapatites have been prepared by solid-state reaction as well as from aqueous solutions and characterized by X-ray diffraction and IR spectroscopic analyses. While the lattice constant *a* of the solid solutions varies linearly with composition, the variation of the lattice constant *c* does not follow Vegard's law but shows a discontinuity at about 50% lead atom content. A similar discontinuity has been observed in the variation of the IR frequencies with composition. Although lead incorporation seems to destabilize the apatite structure, the solid solutions prepared from aqueous media at a lead content around 50% exhibit a high thermal stability. The variation of *c*, thermal stability, as well as the frequencies and intensities of the IR bands of lead–calcium hydroxyapatite are interpreted on the basis of the inhomogeneous lead distribution in the two non-equivalent cation sites of the hydroxyapatite structure.

Hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (hap), which is a good model system for natural apatites, has a structure which can easily accommodate a great variety of substitutions, both cationic and anionic.[1–3] The incorporation of foreign ions affects the crystallinity, morphology, lattice parameters and, as a consequence, the stability of the apatite structure.[4–6] Furthermore, the presence in solution of foreign ions can prevent the formation of the apatitic phase from aqueous systems.

Among the bivalent cations, Mg^{2+}, Mn^{2+}, Fe^{2+}, Co^{2+} and Ni^{2+} promote the formation of β-tricalcium phosphate (β-tcp) at the expense of apatite.[7] These ions, as well as Cu^{2+}, Sn^{2+} and Zn^{2+}, when substituted for calcium or just adsorbed on the apatite surface, cause a reduction in the degree of crystallinity of the apatitic phase.[6,7] Whilst they can be incorporated only to a limited extent into the apatite structure, cadmium, strontium and lead are known to replace calcium in the whole range of composition. The lattice constants of strontium–calcium hydroxyapatites, as well as those of barium–calcium hydroxyapatites (although the latter solid solutions exhibit a zone of immiscibility), vary linearly with the composition between those of the pure end members, according to Vegard's law.[8–10] The observed expansion of the unit cell is coherent with the increase in the ionic radius from calcium to strontium to barium. Cadmium and calcium hydroxyapatite form a continuous series of solid solutions with cell parameters which vary linearly with the composition. The contraction of the lattice constants on increasing cadmium concentration is higher than that expected on the basis of the difference in ionic radius and has been attributed to the more covalent character of the Cd–O interaction. The nature of the cation–oxygen interaction has been invoked also to explain the destabilizing effect of this ion on the apatite structure.[11]

Lead substitution for calcium in the hap structure causes an enlargement of the unit cell, consistent with the difference in ionic radius. However, contradictory data are reported for the variation of the lattice constants with composition: in earlier papers they were reported to vary linearly,[12–14] while more recent results show deviations of the *c* parameter from Vegard's law.[15–17] A non-linear variation of *c* with composition would suggest that lead substitution for calcium is not homogeneous in the two non-equivalent cation sites of the hydroxyapatite structure. Results of powder fitting structure refinements carried out on hydroxyapatites synthesized with different degrees of lead substitution for calcium indicate a clear preference of lead ions for site (2) of the hap structure.[18] The occupancy factors of Pb^{2+} obtained for samples with 20, 45 and 80% Pb atom content indicate that up to about 45% lead fills almost exclusively site (2) and begins to fill site (1) at higher contents. Lead incorporation in the hap structure induces a significant shift of the position of the OH group, which is more evident at lead contents higher than 45%.[18] These data would support and justify the observed deviations of the *c*-axis dimension from Vegard's law.

Herein we report the results of a crystallographic and spectroscopic study carried out on lead-substituted calcium hydroxyapatites in order to investigate the role played by lead on the crystal structure and thermal stability of hydroxyapatite.

Experimental

Calcium hydroxyapatite was prepared by neutralization of a $Ca(OH)_2$ solution with H_3PO_4 under stirring at 100 °C. The product was filtered off, washed with distilled water and dried at 100 °C. Since $Pb(OH)_2$ does not exist as such, lead hydroxyapatite was prepared from $Pb_6O_5(NO_3)_2$ obtained as described by Newkirk and Huges.[19] The compound $Pb_6O_5(NO_3)_2$ was titrated with H_3PO_4 solution under stirring at 100 °C. The powder X-ray diffraction pattern of the product revealed the presence of only a small amount of lead hydroxyapatite with larger amounts of other lead compounds, such as $PbHPO_4$ and some lead oxides. The precipitate was therefore resuspended in distilled water and the pH raised and kept constant at about 11.0 with ammonia solution under heating and stirring for about 2 h. The final precipitate after washing and drying was found to exhibit the powder X-ray pattern characteristic of lead hydroxyapatite.

Lead–calcium hydroxyapatites were prepared following two different methods.

Table 1 Infrared bands (cm^{-1}) for calcium hydroxyapatite, lead hydroxyapatite and lead-substituted calcium hydroxyapatite at a lead content of 50 atom %; $\Delta\nu$ are the variations (%) with respect to the values of calcium hydroxyapatite *

Lead content (atom %)	ν_s(OH)	$\Delta\nu_s$	$\nu_3(PO_4)$	$\Delta\nu_3$	$\nu_3(PO_4)$	$\Delta\nu_3$	$\nu_1(PO_4)$	$\Delta\nu_1$	ν_l(OH)	$\Delta\nu_l$	$\nu_4(PO_4)$	$\Delta\nu_4$	$\nu_4(PO_4)$	$\Delta\nu_4$	$\nu_2(PO_4)$	$\Delta\nu_2$
0	3572	—	1090	—	1040	—	962	—	632	—	601	—	570	—	475	—
50	3560	0.3	1075	1.4	1030	1.0	940	2.3	630(sh)	—	595	1.0	558	2.1	465	2.1
100	3560(sh)	0.3	1035	5.0	975	6.2	930(sh)	3.3	—	—	575	4.3	535	6.1	430	9.5

* ν_s is OH stretch, ν_l is OH libration.

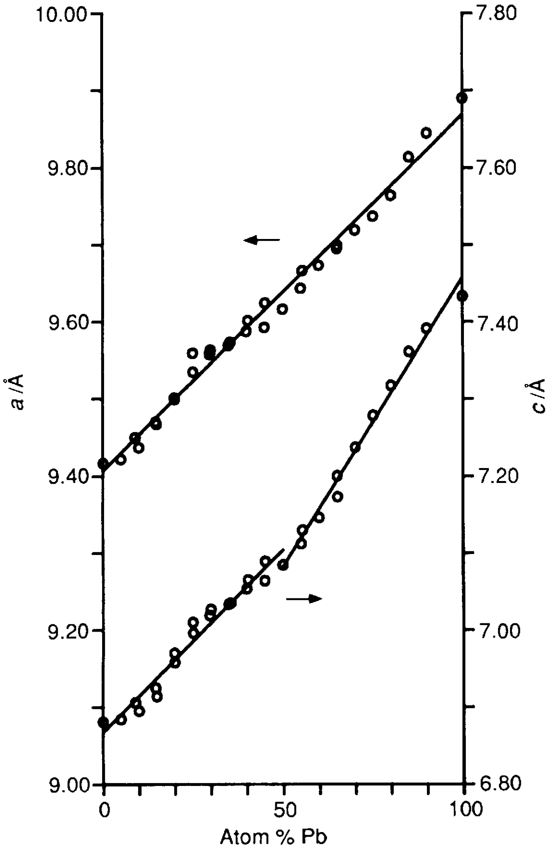

Fig. 1 Plot of the lattice constants of lead–calcium hydroxyapatite solid solution against lead concentration

Solid-state reaction. Mixtures of calcium and lead hydroxyapatites with lead ranging from 0 to 100 atom % were heat treated at 900 °C for about 15 h.

Aqueous solutions. A solution of lead and calcium acetates was added dropwise to a stirring sodium monohydrogenphosphate solution at 100 °C. The lead 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.

Part of the products was heat treated at different temperatures up to 1100 °C for about 15 h.

X-Ray diffraction analysis was carried out by means of a Philips powder PW 1050/81 diffractometer using nickel-filtered Cu-K radiation. The 2θ diffraction range was 10–65° at a scanning speed of 0.5° min^{-1}. The lattice constants were calculated from the well determined positions of more than 10 of the most intense reflections by least-squares refinements.

For IR absorption analysis, *ca.* 1 mg of the powdered samples was intimately mixed with KBr (IR grade) (300 mg) and pelletized under vacuum. The pellets were analysed using a Perkin-Elmer 390 grating spectrophotometer, range 4000–400 cm^{-1}, with a normal slit and a scanning speed of 72 cm^{-1} min^{-1}.

Calcium and lead contents were determined using a Perkin-Elmer 373 atomic absorption spectrophotometer. Phosphorus was determined spectrophotometrically as molybdovanadophosphoric acid.[20]

Results

The synthesis by solid-state reaction of mixtures of calcium and lead hydroxyapatites allowed a continuous series of solid solutions in the whole range of composition to be obtained. The cell parameters *a* and *c* of the apatitic phase obtained by solid-state reaction at 900 °C are plotted in Fig. 1 against lead concentration. The cell parameter *a* varies linearly with lead content, within experimental error, according to equation (1)

$$a = 9.406 + 0.004\,62x\ \text{Å} \quad \sigma = 3.5 \times 10^{-3}\ \text{Å} \qquad (1)$$

obtained by least-squares fit, where x is the lead concentration expressed as atom % lead and the σ values are the standard deviations. On the other hand, the variation of the cell parameter *c* shows a discontinuity at about 50 atom % lead. The equations which describe the *c*-axis variation with composition are (2) and (3).

$$c = 6.866 + 0.004\,75x\ \text{Å} \quad x < 50 \qquad \sigma = 2.0 \times 10^{-3}\ \text{Å} \qquad (2)$$

$$c = 6.707 + 0.007\,50x\ \text{Å} \quad x > 50 \qquad \sigma = 3.5 \times 10^{-3}\ \text{Å} \qquad (3)$$

The infrared absorption spectra of lead-substituted calcium hydroxyapatites reveal a shift of the internal vibration modes of the PO_4^{3-} groups toward lower frequency as the lead content increases in agreement with data of Andres-Verges *et al.*[17] This shift appears more evident at Pb atom contents higher than 50% as can be observed in Table 1. On the other hand on increasing the lead concentration in the solid solutions, the OH^- stretching mode at 3572 cm^{-1} shifts toward lower frequency up to a lead content of about 50% after which its position remains practically constant. Furthermore, the areas of the absorption bands characteristic of OH^- groups decrease on increasing lead content and the absorption band associated with the OH^- librational mode at about 630 cm^{-1}, which does not change appreciably with composition, is no longer detectable at contents higher than 50%.

A continuous series of solid solutions of calcium–lead hydroxyapatites has been obtained also from aqueous media. The lattice parameters of the solid solutions are reported in Table 2 as a function of lead concentration. The values fit well with those described by equations (1)–(3), even if, as expected[21] the apatites from aqueous media exhibit a slightly longer *a*-axis dimension than those prepared by solid-state reaction.

The infrared absorption spectra of these solid solutions confirm the data obtained on samples synthesised by solid-state reaction, even if the broadening of the absorption bands indicates a lower degree of crystallinity.

The crystalline phases, identified by the X-ray powder diffraction patterns of the samples synthesised at 100 °C from aqueous media and heat treated at different temperatures, are listed in Table 3 as a function of lead content. When more than two phases are present the first reported is that present in largest amount. When two phases are present the numbers in parentheses indicate the percentage of β-tcp (JCPDS file no. 9-169) evaluated from comparison of the areas of the diffraction maxima characteristic of the single phase.

Calcium hydroxyapatite exhibits a partial conversion into β-tcp by heat treatment at 1100 °C. On the other hand, on heat treatment at 500 °C, the apatitic phases at a lead substitution for calcium less than 40% convert partially into β-tcp, which is the only crystalline phase present at 1100 °C.

Heat treatment of samples at a lead content higher than 55 atom % induces the conversion of apatite into trilead phosphate (tlp) (JCPDS file no. 22-668) and lead oxide (JCPDS file no. 5-570). Samples with a lead content around 50% do not undergo any thermal conversion, although after heat treatment at 1100 °C their X-ray patterns, as well as those of samples of higher lead contents, are amorphous. The lattice constants of the apatitic phases and of β-tcp obtained by heat treatment of calcium–lead hydroxyapatites do not change appreciably as a function of the heat treatment temperature. Table 4 reports the lattice constants of hap and β-tcp obtained after heat treatment of the solid solutions at 900 °C.

Table 2 Lattice constants of lead–calcium hydroxyapatite solid solutions synthesised from aqueous media at 100 °C

Lead content (atom %)	*a*/Å	*c*/Å	*V*/Å^3
0	9.429(3)	6.879(3)	529.6(3)
14.8	9.48(1)	6.91(2)	538(2)
25.4	9.54(2)	6.94(4)	547(4)
33.9	9.58(1)	6.97(2)	554(2)
43.3	9.68(4)	7.03(4)	571(5)
51.9	9.70(2)	7.11(2)	579(2)
58.5	9.75(1)	7.14(1)	587(2)
65.0	9.75(1)	7.16(1)	590(2)
81.3	9.80(2)	7.28(2)	606(2)
100.0	9.82(1)	7.40(1)	618(2)

Discussion

The replacement of lead for calcium in the apatite structure induces an enlargement of the lattice constants in agreement with the larger ionic radius of lead with respect to that of calcium. The variations of the lattice constants of the solid solutions follow the same laws whether the samples are obtained from aqueous media or by solid-state reaction. As previously suggested[15–17] the variation of the *c* parameter with composition does not follow Vegard's law. Whilst the *a* axis varies linearly with lead concentration according to equation (1), the *c*-axis variation follows equation (2), up to 50 atom % lead and equation (3) from 50 to 100 atom % lead.

The difference in the slope of the two lines (2) and (3), as well as the position of the discontinuity which they define in the variation of the *c*-axis dimension with lead content, can be explained on the basis of the results of the structure refinement of samples with 20, 45 and 80 atom % lead.[18] For samples with less than 50% lead atoms, the heavier atoms occupy mostly site (2). This can be justified by: (*i*) the proximity of the apatitic channels that favours ionic exchange; (*ii*) the 'staggered' position of the metal atoms lying on subsequent layers; and (*iii*) the consequent longer metal (2)–metal (2) distance (4.08 Å in hap) (Fig. 2). On the other hand, when more than 50% of cations are substituted, Pb atoms are forced to occupy site (1): this causes a wider enlargement of the *c* lattice constant due to a rigid superposition of subsequent atoms in columns along the *c* axis and to a shorter metal (1)–metal (1) distance (3.42 Å in hap) (Fig. 2).

Lead substitution for calcium in the hydroxyapatite structure induces a shift of the IR absorption bands characteristic of the PO_4^{3-} internal modes toward lower frequencies in agreement with the increase in the cationic mass. The shift does not exhibit a linear relationship with cationic mass, as happens for calcium,

Table 3 Crystalline phases obtained by heat treatment at different temperatures of the solid solutions synthesised at 100 °C from aqueous media

Lead content (atom %)	Heat treatment temperature (°C) 500	700	900	1100
0	hap	hap	hap	hap/β-tcp(50)
14.8	hap/β-tcp(45)	hap/β-tcp(40)	hap/β-tcp(40)	β-tcp
25.4	hap/β-tcp(30)	hap/β-tcp(30)	hap/β-tcp(30)	β-tcp
33.9	hap/β-tcp(20)	hap/β-tcp(20)	hap/β-tcp(20)	β-tcp
43.3	hap/β-tcp(10)	hap/β-tcp(10)	hap/β-tcp(10)	β-tcp
51.9	hap	hap	hap	—
58.5	hap	hap	hap	—
65.0	hap/tlp/PbO	hap/tlp/PbO	hap/tlp/PbO	—
81.3	hap/tlp/PbO	hap/tlp/PbO	hap/tlp/PbO	—
100.0	hap/tlp/PbO	hap/tlp/PbO	hap/tlp/PbO	—

Table 4 Lattice constants of hap and β-tcp obtained by heat treatment at 900 °C of the solid solutions synthesised at 100 °C

Lead content (atom %)	hap *a*/Å	 *c*/Å	 *V*/Å^3	β-tcp *a*/Å	 *c*/Å	 *V*/Å^3
0	9.423(2)	6.882(2)	529.3(2)	10.432(2)	37.299(5)	3515(4)
14.8	9.556(1)	7.007(2)	554.1(2)	10.449(4)	37.34(2)	3531(2)
25.4	9.585(4)	7.035(5)	559.7(5)	10.460(2)	37.39(2)	3549(1)
33.9	9.619(2)	7.064(2)	566.0(2)	10.473(1)	37.46(1)	3559(1)
43.3	9.652(1)	7.084(1)	571.6(1)	10.512(4)	37.59(3)	3597(4)
51.9	9.675(2)	7.13(2)	577.7(2)	—	—	—
58.5	9.672(2)	7.125(2)	577.2(2)	—	—	—
65.0	9.695(2)	7.172(2)	583.8(3)	—	—	—
81.3	9.719(1)	7.224(2)	590.9(2)	—	—	—
100.0	9.780(7)	7.262(7)	601.6(8)	—	—	—

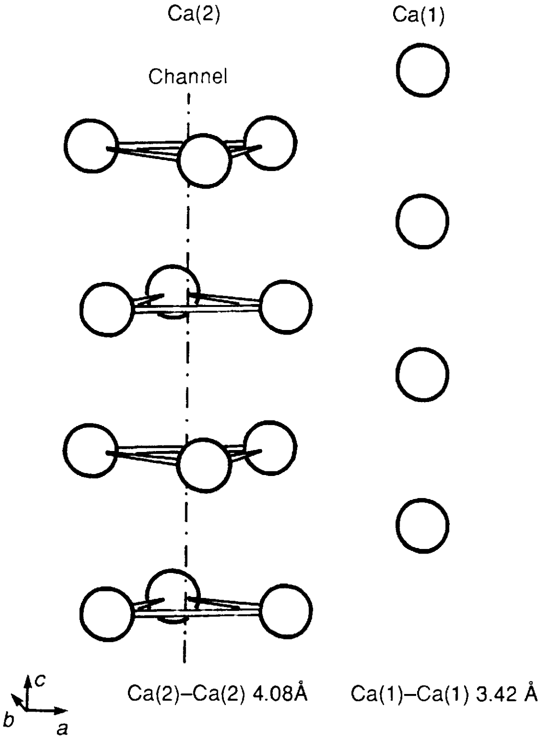

Fig. 2 A view of the calcium sites in the hydroxyapatite structure

strontium and barium apatites,[22] probably due to the more covalent character of lead compared to the alkaline earths. As can be observed in Table 1, the shift of the frequencies of the PO_4^{3-} modes is greater for solid solutions at lead contents higher than 50 atom %, when lead begins to fill site (1). The greater enlargement of the unit cell in the range 50–100% lead substitution induces a greater separation among PO_4^{3-} groups, and therefore a reduced anion–anion repulsion, which can be responsible for the observed greater shift of the PO_4^{3-} frequencies to lower energies. The shift of the OH stretching mode toward lower frequencies when the lead content increases from 0 to 50% is in agreement with the predominant role of M–OH interaction with respect to the $OH \cdots O(PO_3)$ hydrogen bond.[17] On the other hand, this frequency does not change appreciably during the filling of site (1): this can be related to the observed significant shift of OH^- groups from the centre of the Pb(2) triangles[18] which weakens the M–OH interaction. A similar balance between increase in M–OH interaction and enlargement of the unit cell could explain also the almost constant value of the frequency of the OH librational mode in the range 0–50% lead substitution. Furthermore, the displacement of the OH^- groups can be invoked also to justify the decrease in the OH^- band intensities on increasing lead content, which is opposite to that expected on the basis of the more covalent character of lead in comparison to calcium.

The results obtained on the solid solutions prepared from aqueous media indicate that lead incorporation has a destabilizing effect on the apatite structure. The substitution of a few atom % lead provokes the partial thermal conversion of hap into β-tcp. The lattice constants of β-tcp appear enlarged with respect to those of pure β-tcp and increase with increasing lead concentration, suggesting a partial substitution of lead for calcium into this structure. The extent of hap conversion into β-tcp reduces with increasing lead concentration up to the almost complete filling of site (2) which coincides with an unusually high thermal stability of the solid solutions.

On further increase in lead concentration, which begins to fill site (1), the stability of the solid solutions decreases, as shown the thermal conversion of the apatitic phases into tlp and PbO. In contrast with other substituted hydroxyapatites, for which the extent of conversion into other crystalline phases increases with increasing temperature of heat treatment,[11,21,23] the relative amounts of β-tcp, tlp and PbO obtained by thermal conversion of lead–calcium hydroxyapatite do not change appreciably in the range 500–900 °C.

Solid solutions at lead contents lower than 40 atom % convert completely into β-tcp when heat treated at 1100 °C. At the same temperature, the solid solutions at a higher lead content melt, in agreement with the lower melting point of lead apatite with respect to calcium apatite,[24] and they become amorphous, as shown by means of powder X-ray diffraction analysis after cooling.

In conclusion, the variation of the *c*-axis dimension, thermal stability, as well as frequencies and intensities of the IR absorption bands of lead–calcium hydroxyapatites cannot be justified on the basis of the difference in ionic radius and nature of the cation–oxygen interaction alone, but can be accounted for more completely by the structural differences caused by the inhomogeneous lead distribution in the two non-equivalent cation sites of the hydroxyapatite structure.

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