Stoichiometry of Na^+- and CO_3^{2-}-Containing Apatites Obtained by Hydrolysis of Monetite

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In this study, a series of Na^+- and CO_3^{2-}-containing calcium hydroxyapatites were prepared under homogeneous precipitation conditions by the hydrolysis of $CaHPO_4$ in Na_2CO_3 solutions. A chemical and physical analysis showed that the precipitates were single-phase and well-crystalline B-type carbonated apatites with a carbonate content ranging from 8 to 20 wt %. However, the samples still contained an appreciable amount of water even after prolonged drying under vacuum at 25 °C. On the basis of their relative composition and the results of the physical analysis it was found that the predominant substitution mechanisms responsible for the incorporation of Na^+ and CO_3^{2-} in $Ca_{10}(PO_4)_6(OH)_2$ are $Ca^{2+} + PO_4^{3-} + OH^- \leftrightarrow V^{Ca} + CO_3^{2-} + V^{OH}$ and $Ca^{2+} + PO_4^{3-} \leftrightarrow Na^+ + CO_3^{2-}$, where V^X stands for a vacancy in the X-sublattice. In contrast to the results of other investigations, the ratio of the contributions of these mechanisms to the stoichiometry of the carbonated apatites varies with the total substitution degree of carbonate.

Introduction

Calcium hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (HAp), is generally accepted as a prototype for the apatitic mineral in calcified tissues. In these minerals, however, the lattice ions of HAp are substituted to a considerable extent by other ions, especially CO_3^{2-} and Na^+ so that these minerals should be considered rather as substitutional solid solutions.[2] Such substitutions have an important influence on the crystal chemical, physical, and physicochemical properties of the apatite and, consequently, on the mineralization and demineralization processes of the calcified tissues (for a compilation of the literature, see ref 2). In order to derive the fundamental thermodynamic properties of the solid which determine the course of these processes, the stoichiometry of the solid solution and especially the mechanisms by which CO_3^{2-} and Na^+ are incorporated into the apatite lattice must be known.[2–4] In this respect, a rather large number of investigations have been performed using synthetic samples.

The mechanism for the substitution of OH^- by CO_3^{2-} (so-called A-type carbonate) has been well established.[5,6] The mechanisms proposed in the literature for the substitution of PO_4^{3-} by CO_3^{2-} (so-called B-type carbonate) in the absence or in the presence of Na^+, however, are numerous and not consistent (see Table III and, for a critical evaluation, ref 2). Such variability can be attributed partly to the inherent difference in the methods used for the preparation of the (Na^+- and) CO_3^{2-}-containing apatites ((N)CAp's), syntheses based on solid-state reactions at high temperatures,[7–9] hydrothermal syntheses,[10] and preparations using heterogeneous[11–19] or homogeneous[20,21] precipitation methods. Whereas syntheses at high temperatures generally result in well-crystalline, single phase and homogeneous solids due to solid-state diffusion, the composition of samples obtained by heterogeneous precipitation methods apparently is more difficult to control. In fact, the latter methods, consisting of the addition of reagent solution(s) to a mother liquor, result in a fast precipitation due to the relatively high addition speed and the high local supersaturation. Consequently, the composition and the crystallographic and crystal chemical properties of the precipitates will critically depend on the prevailing precipitation conditions so that these properties may change from experiment to experiment within the same investigation as well as from investigator to investigator. This is reflected by the scatter in the experiments of LeGeros *et al.*[11] and Bonel *et al.*[15] as well as by some specific experiments performed by Labarthe *et al.*,[13] Okazaki *et al.*,[16] Vignoles *et al.*,[17] and Nelson et al.[18] In addition, the use of reagents containing ions apart from calcium, phosphate, sodium, and carbonate and incomplete analyses of the solids could result in erratic interpretations of the substitution mechanisms.[12,19]

Local supersaturation inherent to heterogeneous precipitation methods can be kept at a minimum when the reagents are generated slowly in the solution, i.e. by precipitation from homogeneous solution.[22] Such slow, homogeneous precipitation can be obtained by the hydrolysis of a more acid calcium phosphate to apatite, e.g. $CaHPO_4$ (monetite)[20] or $Ca_8H_2(PO_4)_6{\cdot}5H_2O$ (octacalcium phosphate or OCP).[21] As during the hydrolysis of OCP an epitaxial overgrowth of NCAp on the OCP crystals can occur,[21,23] the hydrolysis of monetite might be preferred. Some interesting work in this field was performed by LeGeros *et al.*,[20] who studied some physical properties of NCAp obtained by the conversion of monetite. However, little evidence was given for

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the substitution mechanisms of Na^+ and CO_3^{2-} in the apatite as an accurate and complete chemical analysis was not performed.

In the present study, NCAp's were prepared by the hydrolysis of monetite in Na_2CO_3 solutions, thus restricting the formation of NCAp to the simple system $Ca(OH)_2$–H_3PO_4–Na_2CO_3–H_2O. On the basis of a physical and chemical characterization of the samples, an attempt was made to deduce the substitution mechanisms responsible for the incorporation of Na^+ and CO_3^{2-} in HAp.

Experimental Section

Preparation of NCAp. The NCAp's were prepared according to the method originally proposed by LeGeros *et al.*[20] According to this method 1 g of monetite (Mallinckrodt AR grade; chemical analysis yields (29.34 ± 0.06) wt % Ca and (22.59 ± 0.05) wt % P with a molar Ca/P ratio of 1.004 ± 0.004) was hydrolyzed at 95 °C in a 1-L Na_2CO_3 solution with a concentration c_{nc} ranging from 0.010 to 0.250 M. The suspension was continuously and thoroughly stirred for 5 h, and precautions were taken to prevent a CO_2 contamination from the atmosphere. In a previous study,[24] it was found that under these conditions a complete hydrolysis of monetite occurs at pH $\cong$ 10 with the formation of a single-phase CAp. The precipitates were then filtered, thoroughly washed with hot distilled water (±95 °C) and finally dried under vacuum at 25 °C until a constant weight was obtained.

Chemical Analysis. The calcium content of the precipitates was determined by a complexometric titration with ethylenediaminetetraacetic acid,[25] and the phosphorus content spectrophotometrically as the orthophosphate by using a slight modification of the method of Brabson *et al.*[26] The sodium content of the samples was determined by atomic absorption spectrophotometry. The method of Abresch and Lemm[27,28] was adapted for the determination of the carbonate content. The method consists of a coulometric titration of the carbon dioxide evoluted from an acidified aqueous solution of the apatite. The relative uncertainties on the amount Ca, P, CO_3, and Na analyzed were determined as 0.2, 0.2, 2, and 2%, respectively.

Physical Analysis. X-ray powder diffraction patterns of the samples were recorded by step-scanning using a microprocessor-controlled diffractometer system (Philips PW 1830). Ni-filtered copper $K\alpha$ radiation was used with an PW1836 automatic divergence slit and a graphite monochromator. The dimensions a and c of the hexagonal unit cell of the apatites were calculated from the position of the most intense and sharp reflections (usually $n > 19$) using a least squares refinement program. The experimental errors on a and c were estimated as 0.0006 and 0.0002 nm, respectively. IR spectra of the samples dispersed in CsBr tablets were recorded using a Pye Unicam 9512 dispersive spectrophotometer. The density of the samples was measured with a helium micropycnometer of Quantachrome Corp. with an accuracy of 0.2%.

Results

Chemical Composition. The chemical composition of the precipitates is summarized in Table I as a function of the Na_2CO_3 concentration in the solution. The hydroxide content of the NCAp's was calculated on the basis of the electroneutrality condition and the experimentally determined contents of Ca, P, Na, and CO_3. The last column of Table I gives the total mass balance as calculated from the equation

$$\sum\% = \%\,Ca + \frac{\%\,P \cdot M_{PO_4}}{M_P} + \%\,CO_3 + \%\,Na + \%\,OH \qquad (1)$$

with M_X the atomic or ionic mass of X. For the calculation of % OH and Σ%, it is assumed that all the phosphorus of the samples is present as PO_4^{3-}. The errors on % OH and Σ% were estimated by means of the error propagation theory. The data in Table I show that the Ca, P, and OH contents of the samples decrease whereas the CO_3 and Na contents increase as the Na_2CO_3 concentration in the solution increases. The values of Σ%, being significantly lower than 100%, suggest that the samples still contain approximately 5% water.

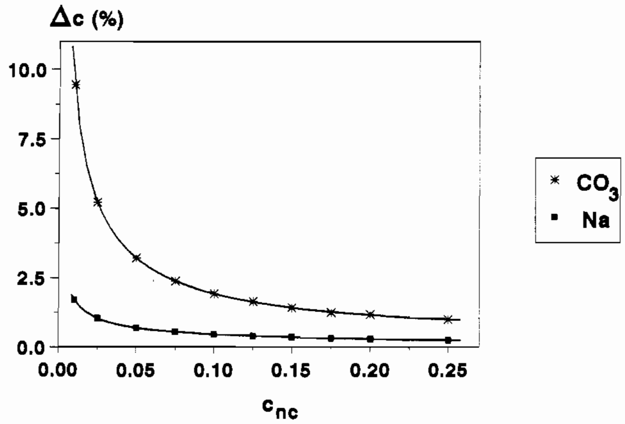

Figure 1. Relative decrease (Δc) of the concentration of Na^+ (■) and CO_3^{2-} (∗) in the aqueous solution after the hydrolysis of monetite as a function of the initial concentration c_{nc} (M) of Na_2CO_3.

Table I. Chemical Composition (Weight Percent) and Total Mass Balance Σ% of the Precipitates Obtained by the Hydrolysis of Monetite in Solutions Containing c_{nc} M Na_2CO_3

		%					
sample	c_{nc}	Ca	P	CO_3	Na	OH	Σ%
1	0.010	36.48	15.58	7.94	1.08	1.59 ± 0.12	94.86 ± 0.16
2	0.025	36.07	14.69	10.9	1.66	1.49 ± 0.13	95.12 ± 0.18
3	0.050	35.47	14.02	13.3	2.25	1.14 ± 0.17	95.14 ± 0.20
4	0.075	35.21	13.55	14.8	2.59	1.10 ± 0.19	95.23 ± 0.21
5	0.100	34.82	13.13	16.0	2.88	1.00 ± 0.20	94.93 ± 0.22
6	0.125	34.61	12.84	16.9	3.17	0.99 ± 0.21	95.03 ± 0.23
7	0.150	34.46	12.63	17.7	3.35	0.90 ± 0.22	95.11 ± 0.23
8	0.175	34.25	12.39	18.4	3.53	0.83 ± 0.23	95.02 ± 0.24
9	0.200	34.15	12.18	19.3	3.67	0.72 ± 0.24	95.14 ± 0.25
10	0.250	34.14	11.76	20.7	3.83	0.70 ± 0.25	95.43 ± 0.26

On the basis of the amount of precipitate obtained by the hydrolysis and its carbonate and sodium content, one can calculate the changes in CO_3^{2-} and Na^+ concentration in the solution during the precipitation. The results of such calculation are represented in Figure 1. According to Figure 1 the relative change of the Na^+ concentration in the aqueous solution is small and hardly depends on c_{nc}, while that of the CO_3^{2-} concentration shows a somewhat more pronounced dependency on c_{nc}. However, except for sample 1, the relative decrease does not exceed 5%. This clearly demonstrates that the hydrolysis of monetite in Na_2CO_3-containing solutions, as performed in the present study, is a very suitable method for the preparation of NCAp under homogeneous precipitation conditions at nearly constant levels of CO_3^{2-} and Na^+ concentrations in the solution.

Physical Analysis. Figure 2 represents the X-ray diffraction pattern of sample 5, which is representative for all samples prepared in this study. No extraneous peaks attributable to phases other than apatite could be found in the diffractograms, and all reflections can be attributed to the hexagonal crystal form of hydroxyapatite (ASTM Powder Diffraction File No. 9-432), corroborating that the homogeneous precipitation method used in the present study is suitable for the preparation of NCAp, containing no other phase. The diffraction peaks are relatively sharp, which suggests that the NCAp's have a relatively high crystallinity.

As the CO_3 content of the apatites increases, some shifts of the peaks can be observed, reflecting a change in unit cell dimensions due to the incorporation of CO_3^{2-} and Na^+. The lattice parameters a and c of the NCAp's are given in Figure 3 as a function of the CO_3 content. The figure shows that both lattice parameters vary

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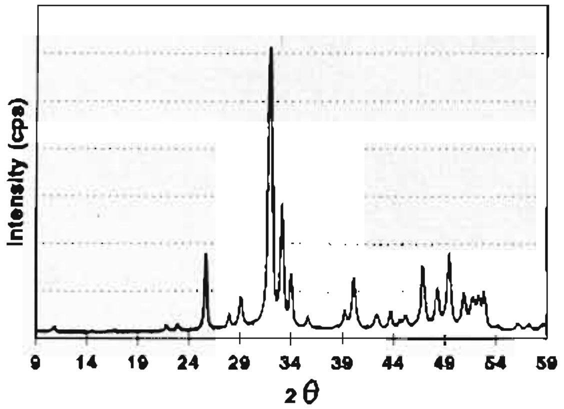

Figure 2. X-ray diffraction pattern of sample 5.

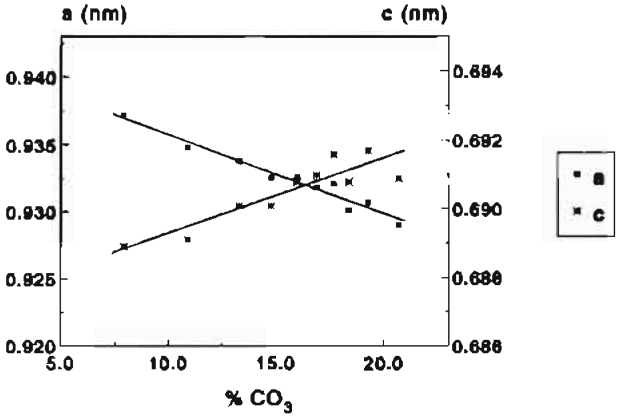

Figure 3. Lattice parameters *a* (■) and *c* (✱) versus CO_3 content (weight percent) of NCAp.

linearly with the carbonate content. This is confirmed by a weighted regression analysis, which shows that the relation between these parameters is linear at the 95% significance level and is given by the equations

$$a = (0.9417 \pm 0.0016) - (5.9 \pm 1.0) \times 10^{-4}[\%\ CO_3] \quad (2)$$

and

$$c = (0.6871 \pm 0.0013) + (2.2 \pm 0.8) \times 10^{-4}[\%\ CO_3] \quad (3)$$

where the uncertainties on the parameters correspond to the 95% confidence level. Equations 2 and 3 are represented in Figure 3 by the full lines. According to eqs 2 and 3 the *a* and *c* dimensions for $\%\ CO_3 = 0$ equal the values for pure HAp within experimental error.[29] Moreover, the *a* axis systematically decreases and the *c* axis increases with an increasing carbonate content. The variation of the lattic dimensions with the carbonate content according to eqs 2 and 3 corresponds well with that calculated from the data of LeGeros *et al*[20], i.e.

$$a = (0.9442 \pm 0.0014) - (6.3 \pm 1.0) \times 10^{-4}[\%\ CO_3] \quad (4)$$

and

$$c = (0.6871 \pm 0.0009) + (1.7 \pm 0.7) \times 10^{-4}[\%\ CO_3] \quad (5)$$

Such typical variation of *a* and *c* with the carbonate content indicates that CO_3^{2-} substitutes a PO_4^{3-} ion in the apatite lattice as is found in several studies.[2,29] A-type carbonate or CO_3^{2-} substituting for OH^-, on the other hand, would cause an expansion of the *a*-axis dimension and a slight contraction of the *c*-axis dimension,[2,29] which is not observed.

Figure 4 presents the IR spectrum of samples 1, 5, and 10, which are representative for all NCAp's prepared in the present study. The spectra are characteristic for CO_3^{2-}-containing apatites. The figure shows that the bands are relatively sharp and well resolved indicating a high degree of crysallinity of the solids. Specific absorptions of PO_4^{3-} vibrations are observed in the ranges 960–1100 and 570–610 cm^{-1}. Absorptions of HPO_4^{2-} ions[30] could not be detected indicating that the phosphorus is nearly completely present as PO_4^{3-} in the apatite lattice. A chemical analysis of the HPO_4^{2-} content of some representative samples (i.e. samples 1, 2, 5, and 10) according to the method described by Meyer and Fowler[31] further shows that these samples do not contain HPO_4^{2-} within experimental error indicating that at most 0.2% of the total amount of phosphorus determined would be present as HPO_4^{2-}. These results again confirm the complete hydrolysis of monetite under the conditions used in the present study[24] and substantiate the assumption made for the calculation of % OH and Σ%. The stretching vibration (~3572 cm^{-1}) and the libration (~633 cm^{-1}) of OH^- can hardly be detected in the IR spectra. The visibility of these bands even decreases with increasing CO_3 content of the NCAp's. This suggests that OH^- ions might be involved in the substitution mechanisms responsible for the incorporation of Na^+ and CO_3^{2-} in the apatites. Moreover, the OH^- band near 3572 cm^{-1} is masked by a broad band. This band, together with an absorption at ~1635 cm^{-1}, can be assigned to H_2O. Typical absorption bands of CO_3^{2-} are observed at ~873 and ~1415 cm^{-1} and between 1464 and 1480 cm^{-1}, which indicates that the NCAp's contain CO_3^{2-} on PO_4^{3-} lattice sites.[2] IR absorptions arising from the vibrations of CO_3^{2-} on OH^- lattice sites could not be detected so that the NCAp's can be considered as pure B-type CAp's in agreement with the conclusions made on the basis of the lattice dimensions. The relative intensities of the CO_3^{2-} bands increase with increasing carbonate content of the sample.

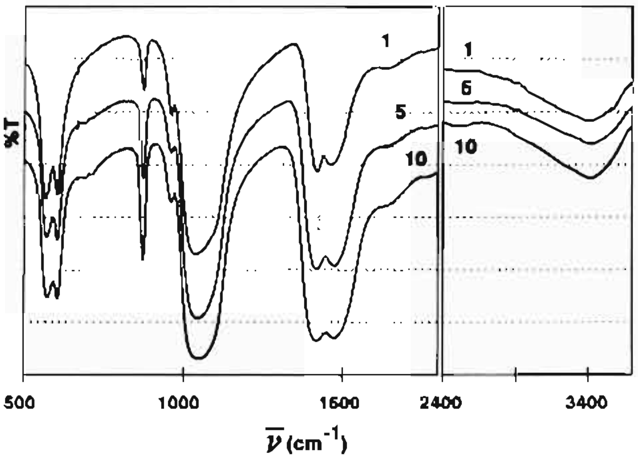

Figure 4. IR spectra of samples 1, 5, and 10 (percent transmission % *T* versus wave number $\bar{\nu}$ (cm^{-1})).

The density of the samples as a function of their molar Ca/P ratio is represented in Figure 5. It can be seen that, with increasing Ca/P ratio and, consequently, with increasing CO_3 content of the apatite, the density decreases. A weighted regression analysis shows that the density as a function of Ca/P is represented at the 95% significance level by the equation

$$\rho = (5.6 \pm 1.0) - (2.5 \pm 1.0)[Ca/P] + (0.52 \pm 0.25)[Ca/P]^2 \quad (6)$$

The dependency given by eq 6 can be ascribed to the substitution of the Ca^{2+} and PO_4^{3-} lattice ions by the Na^+ and CO_3^{2-} ions with a smaller ionic mass.

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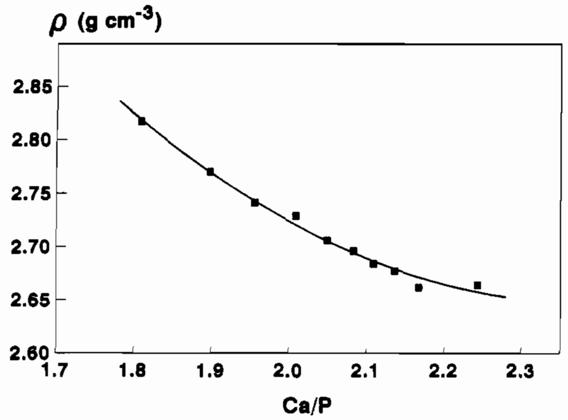

Figure 5. Density ρ (g cm^{-3}) of NCAp as a function of the molar Ca/P ratio of the solid.

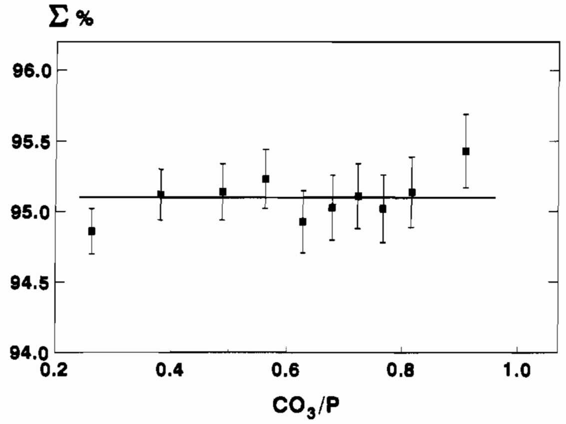

Figure 6. Total mass balance $\Sigma\%$ as a function of the molar CO_3/P ratio for the NCAp samples of the present study.

Discussion

From the chemical composition of the apatites, their density, and the lattice dimensions, the composition of the unit cell of the NCAp's could be calculated. However, the results of the chemical analysis as well as the IR spectra clearly demonstrate that the NCAp's prepared in the present study still contain an appreciable amount of water which cannot be removed by drying at 25 °C under vacuum. Such water can be adsorbed on the crystals, occluded between the crystals, or incorporated in the crystal lattice on vacant lattice sites.[32] Nonstructural, i.e. adsorbed or occluded, water systematically causes an apparent decrease of the density as well as of the ionic contents in comparison to water-free apatites. Consequently, a calculation of the content of the unit cell based on such quantities would result in an underestimation of the number of each type of ion per unit cell.

Structural water is thought to be located on vacant lattice sites resulting from either the incorporation of carbonate[15] or a defective HAp stoichiometry.[30] The present NCAp's contain no HPO_4^{2-} ions. Moreover, the apparent water content as reflected by $\Sigma\%$ (eq 1) is independent of the carbonate content. This is illustrated in Figure 6, where $\Sigma\%$ is given as a function of the molar CO_3/P ratio with a mean represented by the full line. Consequently, it is less plausible that all the moisture present is structural water. Most likely, part of the water is nonstructural and higher drying temperatures are probably required to remove it. This was not attempted in this study, as several investigators demonstrate that a drying process at higher temperatures of synthetic and/or natural apatites cannot be completed without severe constitutional changes, e.g. CO_3^{2-} loss.[17,33-35]

Table II. Fundamental Substitution Mechanisms for Na^+ and B-type CO_3^{2-} in HAp[a]

symbol	fundamental mechanism
I	$Ca^{2+} + PO_4^{3-} + OH^- \leftrightarrow V^{Ca} + CO_3^{2-} + V^{OH}$
II	$Ca^{2+} + 2PO_4^{3-} \leftrightarrow V^{Ca} + 2CO_3^{2-}$
III	$Ca^{2+} + PO_4^{3-} \leftrightarrow Na^+ + CO_3^{2-}$
IV	$Ca^{2+} + OH^- \leftrightarrow Na^+ + V^{OH}$
V	$PO_4^{3-} \leftrightarrow CO_3^{2-} + OH^-$

[a] V^X stands for a vacancy in the X-sublattice.

Although the absolute content of the unit cell cannot be calculated on the basis of the present results, some interesting conclusions can be drawn from the relative composition of the NCAp's prepared in this study.

On the basis of sterical and electrostatical arguments, it can be deduced in a general way that five fundamental substitution mechanisms can account theoretically for the incorporation of Na^+ and/or B-type CO_3^{2-} in HAp.[35] They are given in Table II. The stoichiometry of NCAp can then be considered as the result of the occurrence of one or more of these mechanisms. The contribution of each mechanism will depend on their effect on the relative stability and on the preparation conditions of NCAp. A combination or "coupling" of different mechanisms in a fixed proportion can lead to the definition of an apparently new substitution mechanism. This is illustrated in Table III, where the most important substitution mechanisms proposed in the literature were analyzed with respect to the contribution of the fundamental mechanisms for Na^+ and/or B-type CO_3^{2-} incorporation given in Table II. In Figures 7–9 the molar CO_3/P, Na/P, and OH/P ratios of the NCAp's prepared in the present study are given as a function of the molar Ca/P ratio. A weighted regression analysis shows that there is a linear relationship between these parameters at the 95% significance level which is represented by the equations

$$CO_3/P = -(2.51 \pm 0.10) + (1.53 \pm 0.05)[Ca/P] \quad (7)$$

$$Na/P = -(1.46 \pm 0.15) + (0.86 \pm 0.07)[Ca/P] \quad (8)$$

and

$$OH/P = (0.55 \pm 0.10) - (0.20 \pm 0.05)[Ca/P] \quad (9)$$

The uncertainties on the parameters of eqs 7 to 9 correspond to the 95% confidence level. The full lines in Figures 7–9 respectively represent eqs 7 to 9, whereas the dashed lines give the relation between the molar ratios which can be expected on the basis of the mechanisms mentioned in Tables II and III.

It is clear that the lines representing the experimental points (eqs 7–9) do not coincide with one and the same fundamental mechanism (mechanisms I–V, Table II) in each of the Figures 7–9. This means that the incorporation of Na^+ and CO_3^{2-} in the NCAp's prepared by the hydrolysis of monetite is accounted for by several fundamental mechanisms. Moreover, no coincidence is observed between the lines representing the experimental points and a line corresponding to a combined or "coupled" substitution mechanism (mechanism D, E, or F, Table III) in each of the Figures 7–9. This indicates that the constant ratio of the contributions of different fundamental mechanisms to mechanisms D, E, and F should probably be ascribed to an inadequate approximation or to some casual results in the case of precipitated NCAp's. Besides, Figure 9 and eq 9 show that the line describing the experimental points does not include the point with coordinates (10/6; 2/6) corresponding to pure HAp. This confirms that no constant ratio exists between the contributions of all fundamental substitution mechanisms. Obviously, these mechanisms can occur independently from one another.

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Table III. Analysis of Substitution Mechanisms for Na^+ and B-Type CO_3^{2-} in HAp Proposed in the Literature[a]

symbol	mechanism	fundamental mechanism(s)[b]	ref
A	$Ca^{2+} + PO_4^{3-} + OH^- \leftrightarrow V^{Ca} + CO_3^{2-} + V^{OH}$	I	13
B	$Ca^{2+} + 2PO_4^{3-} \leftrightarrow V^{Ca} + 2CO_3^{2-}$	II	10
C	$Ca^{2+} + PO_4^{3-} \leftrightarrow Na^+ + CO_3^{2-}$	III	8, 11, 21
D	$2Ca^{2+} + 3PO_4^{3-} + OH^- \leftrightarrow 2V^{Ca} + 3CO_3^{2-} + V^{OH}$	I + II (1:1)	9
E	$3Ca^{2+} + 3PO_4^{3-} + OH^- \leftrightarrow 2Na^+ + V^{Ca} + 3CO_3^{2-} + V^{OH}$	I + III (1:2	14
F	$2Ca^{2+} + PO_4^{3-} + OH^- \leftrightarrow 2Na^+ + CO_3^{2-} + V^{OH}$	III + IV (1:1)	12

[a] V^X stands for a vacancy in the X-sublattice. [b] The ratio of the numbers between parentheses corresponds to the ratio of the contributions of the fundamental mechanisms from Table II to the mechanism considered in the second column.

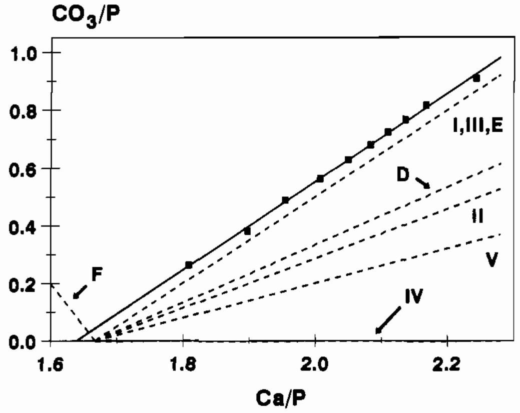

Figure 7. Molar CO_3/P ratio as a function of the molar Ca/P ratio for the NCAp samples of the present study (-■-) and for the substitution mechanisms given in Tables II and III (- - -).

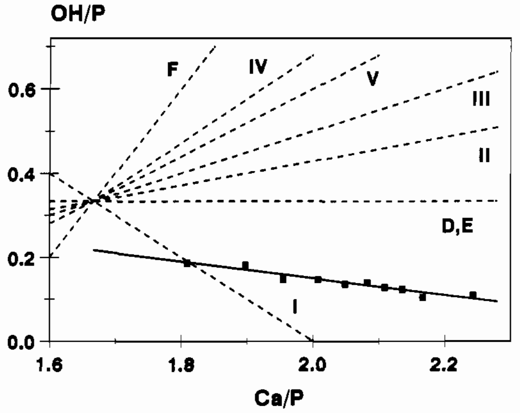

Figure 9. Molar OH/P ratio as a function of the molar Ca/P ratio for the NCAp samples of the present study (-■-) and for the substitution mechanisms given in Tables II and III (- - -).

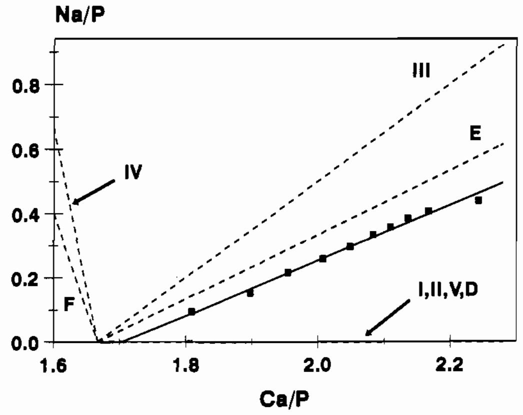

Figure 8. Molar Na/P ratio as a function of the molar Ca/P ratio for the NCAp samples of the present study (-■-) and for the substitution mechanisms given in Tables II and III (- - -).

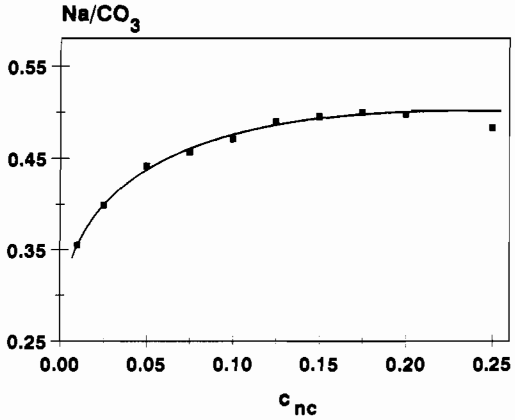

Figure 10. Molar Na/CO_3 ratio for the NCAp samples as a function of the concentration c_{nc} (M) of Na_2CO_3.

On the other hand, from Figures 7 and 8 and eqs 7 and 8, it is clear that the experimental lines include the point (10/6; 0) corresponding to pure HAp within experimental error. Moreover, eq 7 equals eq 10, which describes the relationship between the

$$CO_3/P = -{}^5/_2 + {}^3/_2[Ca/P] \qquad (10)$$

CO_3/P and the Ca/P ratio on the basis of the mechanisms I and III. This indicates that the fundamental substitution mechanisms I and III are predominant for the incorporation of CO_3^{2-} and Na^+ in NCAp prepared by the hydrolysis of monetite. Since the dependencies of the Na/P ratio and the OH/P ratio on the Ca/P ratio differ for these two mechanisms (see Figures 8 and 9), it is hardly surprising that the experimental points do not lie on one of the theoretical lines in these figures. Moreover, the linear relationship between the molar ratios as given by eqs 7–9 indicates that mechanisms I and III appear in *every* apatite of the series. Indeed, if one of these mechanisms would appear only from a certain substitution degree on, the linearity would be perturbed.

The occurrence of mechanism I is in agreement with the decreasing OH content (Table I) and with the decreasing intensity of the OH^- IR bands (Figure 4) as a function of the CO_3 content of the NCAp's. Due to this individual CO_3^{2-} incorporation, the CO_3/P ratio exceeds the Na/P ratio for all samples, as is shown by a comparison of Figures 7 and 8. Moreover, a positive correlation apparently exists between the CO_3/P ratio and the Na/P ratio of the precipitated NCAp's, as could be expected on the basis of mechanism III. Indeed, a weighted polynomial regression reveals a linear relationship between these two parameters according to the equation

$$Na/P = -(0.056 \pm 0.020) + (0.563 \pm 0.030)[CO_3/P] \qquad (11)$$

where the errors on the parameters correspond to the 95% confidence level. Still, one should keep in mind that Na_2CO_3 is used as a Na^+- and CO_3^{2-}-containing reagent. Consequently, the variations of the Na^+ and CO_3^{2-} concentration in the solution are correlated and the Na^+ and CO_3^{2-} incorporation cannot be considered separately. Equation 11 indicates that the Na/CO_3 molar ratio of the samples changes significantly as a function of the substitution degree. This is more clearly illustrated in Figure 10, where Na/CO_3 is given as a function of the Na_2CO_3 concentration in the solution. This result again shows that the ratio of the contributions of the mechanisms I and III is not constant. Whether these mechanisms mutually influence each other crystal chemically must be further investigated.

Conclusion

The homogeneous precipitation method used in the present study is very suitable for the preparation of a coherent series of NCAp's. This is clearly demonstrated by the small scatter of the results of the chemical and physical analyses of the samples (Figures 3, 5, and 7–10) as compared to some literature data.[7,12–15,17,21] The predominant mechanisms responsible for the Na^+ and CO_3^{2-} incorporation in these apatites, i.e. [$Ca^{2+} + PO_4^{3-} + OH^- \leftrightarrow V^{Ca} + CO_3^{2-} + V^{OH}$] and [$Ca^{2+} + PO_4^{3-} \leftrightarrow Na^+ + CO_3^{2-}$], were deduced in the most general way: every fundamental substitution mechanism was considered. This is in opposition to previous studies, in which just a few fundamental mechanisms were taken into account[7–11,13–15,17,21] or coupled and/or nonfundamental mechanisms were postulated.[7,9,12–15] Moreover, it was shown that the predominant substitution mechanisms can be deduced on the basis of the *relative* composition of the apatites only. In the past, the presumed *absolute* composition has mostly been used for this purpose.[11–15,17,21] Still, either the presence of nonconstitutional water or important constitutional changes due to a foregoing drying process might have falsified the results for samples prepared in aqueous media.

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