Journal of Fluorine Chemistry, 41 (1988) 53–64

FLUORIDE-CATION INTERACTIONS IN THE FORMATION AND STABILITY OF APATITES

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SUMMARY

The effect of fluoride, F^-, on the formation and stability of the apatites, with and without the simultaneous presence of some cations M* (M* = Al^{3+}, Mg^{2+}, Sr^{2+} or Zn^{2+}) in the solution were investigated.

The preliminary findings were: (a) the cations, M*, when present in low levels in solution, had negative effects on the properties of apatite e.g., caused lower crystallinity, lower Ca/P ratios, higher HPO_4/PO_4, and higher extent of dissolution in an acid buffer; (b) when only F^- ions were present in the precipitation solution, F in the apatite formed had positive effect: greater crystallinity, higher Ca/P, lower HPO_4/PO_4, lower extent of dissolution; and (c) the simultaneous presence of F with the cations, M*, minimized their negative effects and suppressed the formation of Mg-substituted β-TCP.

These preliminary results suggest that in biological systems, the simultaneous presence of F^- ions with aluminum, magnesium, strontium or zinc ions will minimize the otherwise negative effects of these cations on the formation and stability of the biological apatites (enamel, dentin, bone mineral).

INTRODUCTION

The presence of Fluoride, F^-, ions in solution has been associated with enhanced formation of biological and synthetic apatites [1-5], causing the formation of F-substituted apatites which are structurally stable [6-8], have greater crystallinity (reflecting larger crystal size and lower internal strain [4,5,9-12] and less susceptible to acid dissolution than F-free apatites [5,10,13-16]. Some cations (e.g., aluminum, magnesium, strontium or zinc) when present in solution, disturb or inhibit the crystal growth of synthetic apatites [17-22]. Some of these cations have been associated with dental caries [23-25], calculus formation [21,26,27], pathological calcification and bone diseases [28-31].

The purpose of this study was to determine the effect of F^- ions, when present alone or simultaneously with other cations (aluminum, magnesium, strontium or zinc) on the formation and stability of synthetic apatites and thereby gain insights into the fluoride effect under similar conditions in biological systems. Preliminary results are presented in this paper.

MATERIALS AND METHODS

Syntheses

Solution A (containing Ca^{2+} or Ca^{2+} + M*, where M* = Al^{3+}, Mg^{2+}, Sr^{2+}, or Zn^{2+}) was added dropwise into the continuously stirred **Solution B** (containing phosphate, P, or P + F) maintained at 95°C during the 4h period of precipitation and digestion. **Solution** A was 250 ml, 0.04 mol/L with respect to Ca^{2+} or Ca^{2+} + M*. The solution M*/Ca molar ratios were 0/1, 0.02/1 and 0.08/1. **Solution** B was 100 ml Na_2HPO_4, 0.1 mol/L, with or without F^-, made up to 750 ml with distilled H_2O; initial pH adjusted to 7.5. When F was present in **Solution** B, the F/P ratio was 0.2/1. To determine the effect of only F in the absence of M*, the solution F/P molar ratios were 0/1, 0.01/1, 0.05/1, 0.1/1, 0.2/1 and 0.3/1 [9,17]. At least triplicate preparations were made for each type of solution composition.

Analyses

(a) **X-ray diffraction analyses** were made on a Philips Electronics instrument, APD3520, x-rays generated at 40 kV and 20 mA from a high intensity fine-focus Cu target X-ray tube, using a graphi E single crystal monochromator, scanning speed, 1/8 deg 2θ per min. For lattice parameter measurements, NaCl was used as internal standard and the a- and the c-axes calculated from the (410), (300), (004) and (002) reflections [32] with a precision of ± 0.003 A. Crystallinity was determined from the line broadening measurements at half-height, B½, of reflections (002) and (300). The β-TCP/HA ratio in the x-ray diffraction patterns of apatite ignited at 800°C were calculated as previously described [17,33].

(b) Infrared absorption analyses were made on a Perkin-Elmer 983G double grating instrument on KBr pellets pressed at 12,000 psi; sample/KBr (IR grade) ratio of 1 mg/300 mg KBr. The absorption band assignments were according to earlier studies on apatites and related calcium phosphates [4,17,34-37]. The HPO_4/PO_4 absorbance ratios were calculated from the ratio of absorbance intensities at about 864 and 600 cm^{-1}, respectively.

(c) Fluoride analyses were made using the specific F ion electrode method previously described [38]. The values obtained had a relative error of 3%.

(d) Chemical analyses Calcium content was determined using an atomic absorption spectrophotometric method [39]; phosphorus, using a colorimeteric method (40). The precision of the measurements were 2 and 3% relative error, respectively. The Ca/P molar ratios of the apatites were calculated from the chemical data and also from the β-TCP/HA ratios in the x-ray diffraction patterns of the ignited apatites. The formation of β-TCP upon ignition of apatite at 800°C or above is indicative of non-stoichiometric Ca/P ratio and of the HPO_4 in the apatite [17,33,41,42].

(e) Statistical management of data [43] T-tests were used at the 0.05 significance level to discern differences between sample groups. Regression analysis was used to establish correlation relationship between dependent and independent variables. Correlation was significant at the 0.01 confidence level.

Dissolution Experiments

Dissolution experiments were carried out in acetate buffer (0.1 mol/L KAc, pH 5) at 37°C; suspension time, 30 min; solid/solution ratio, 100 mg powdered apatite/25 ml buffer. The solid was filtered off and the buffer solution analyzed for Ca^{2+}. The extent of dissolution was expressed as mM Ca in buffer [14,44].

RESULTS

Effect of Fluoride without M*

Apatites obtained from solutions containing F^- but not M* readily incorporated F^-, the amount of incorporation directly proportional to the solution F concentration (Fig. 1). The F-for-OH substitution in the apatite was reflected in the a-axes ranging from 0.07 to 3.84 ± wt%, confirming results reported previously on F content vs. a-axis of the apatite [6,7,10,15,17,45]. The incorporation of F in the apatite caused the following positive effects: (a) increase in crystallinity as shown by the sharper diffraction peaks and smaller line-broadening of the peaks (Figs. 2B vs 2A):

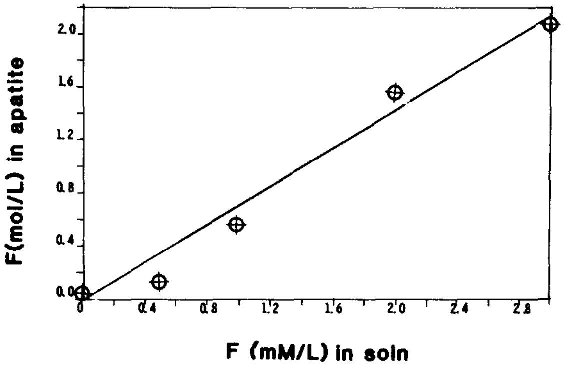

Fig. 1. Direct dependence of F incoporation in the apatite on the solution F^- concentration. The high F incorporation shows the preference of the apatite to form the more stable F-containing apatite.

(b) increase in crystallinity is also reflected in the IR spectra of the F-substituted apatites which show a greater resolution of the PO_4 vibration bands in the regions 1100 to 1200 cm^{-1} (triple bands) and in the region 560 to 600 cm-1 (two bands and a shoulder at about 575 cm^{-1}) as shown in Fig. 3; (c) lower HPO_4/PO_4 ratio as determined from the intensity of the HPO_4 absorption band in their IR absorption spectra (Fig. 3) and from the HPO_4/PO_4 absorbance ratios at 864 and 600 cm^{-1}, respectively (Fig.4);(d)increasing Ca/P molar ratio with increasing F con-

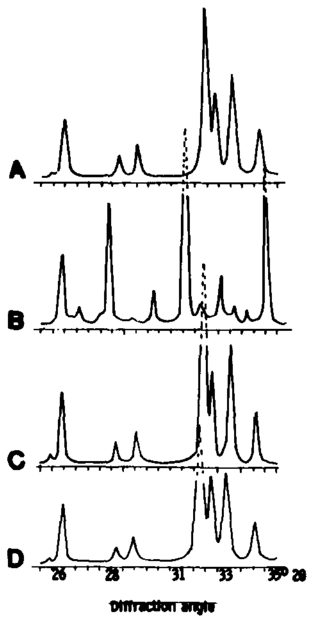

Fig.2. X-ray diffraction patterns of apatites obtained from non-F (A,C) and F-containing (B,D) solutions. C,D were obtained from solutions containing Zn^{2+}. Zn causes lower crystallinity (C vs A), F, greater crystallinity (B vs A; D vs. C).

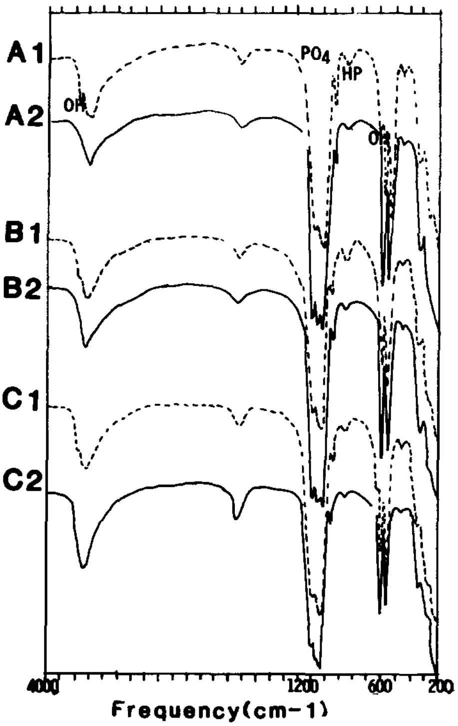

Fig. 3. IR absorption spectra of apatites obtained from non-F (A1,B1,C1) and F-containing (A2,B2,C2) solutions. The IR spectra of A2,B2,C2 show greater resolution of the PO_4 bands, and lower HPO_4(HP) intensities. B and C also contain Sr and Al, respectively.

tent of the apatite, the value increasing toward the stoichiometric value of 1.67 for pure OH^- or F^-apatites, $Ca_{10}(PO_4)_6(OH)_2$ or $Ca_{10}(PO_4)_6F_2$, shown in Fig. 5;

(e) lower β-TCP/HA ratio after ignition at 800°C (Fig. 6C vs Fig. 6A; 10 β TCP/90HA for apatite containing 2.7 wt% F; 48/52 for apatite containing 0.07 wt% F); (f) lower extent of dissolution in acid buffer, confirming other studies [10,14,15,44].

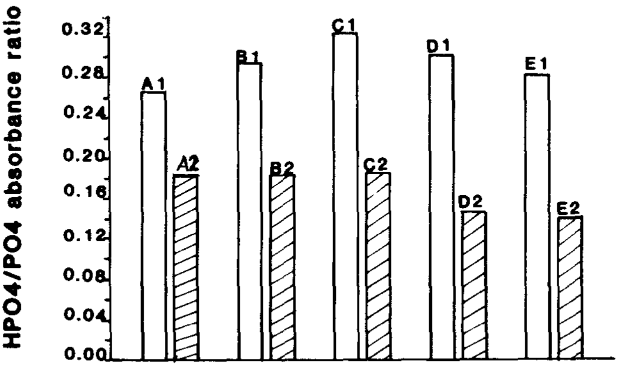

Fig.4. Effect of F on the HPO$_4$/PO$_4$ ratio in the apatites as determined from the HPO$_4$/PO$_4$ absorbance ratio in their IR spectra (Fig. 3). Apatites without F: A1,B1,C1,D1,and E1; with F: A2,B2,C2,D2,E2. E(1,2), from solutions not containing M*; A(1,2), with zinc; B(1,2) with magnesium; C(1,2) with aluminum; D(1,2) with strontium. Solution M*/Ca =.03/1 (A to D)

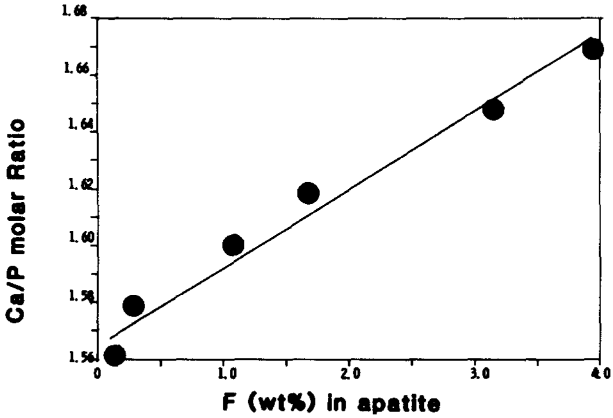

Fig. 5. Increase in Ca/P molar ratio with increasing F content of the apatite. The stoichiometric Ca/P for pure OH- or F-apatite is 1.67.

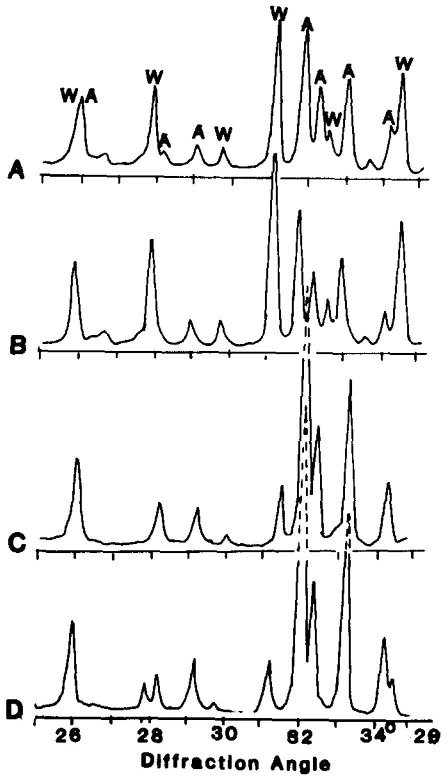

Fig.6. X-ray diffraction patterns of apatites ignited at 800°C. (A) and (D) apatites obtained from solutions without F^- ; (C) and (D), containing F^- ions. (B) and (D) also contain Mg. -TCP (W)/HA ratios calculated were: (A) 48/52; (B) 60/40; (C) 10/90 (D) 15/85.

Effect of M* without F

Apatites prepared in the presence of low levels of aluminum, magnesium or zinc were lower in crystallinity than those prepared in their absence (Fig. 2C compared 2A for the effect of zinc) confirming earlier studies [18]. Similar levels of strontium had no apparent effect on the crystallinity of apatites based on the line broadening measurements in their x-ray diffraction patterns. However, based on their IR absorption spectra (Figs. 3B1, 3C1 compared to 3A1), strontium (Fig. 3B1), aluminum (Fig 3C1) and magnesium [21] caused the formation of apatite with degree of crystal perfection as shown by the lower resolution of the OH (at 3300 and 630 cm^{-1}) absorption bands. Apatites obtained from solutions containing low levels of Mg^{2+}, Zn^{2+}, and Sr^{2+} had lower extent of dissolution compared to apatites obtained in their absence (Table 1) confirming earlier findings on magnesium and strontium effects [41-43]. On the other hand, apatites prepared from different levels of Al^{3+} in solution (0.01 to 0.08 mM/L) demonstrated a lower extent of dissolution reverting back to no effect (Fig. 7).

TABLE I

Effect of Some Cations With and Without F on Some of the Properties of Apatites.

Cations (M)	Crystallinity (X-ray)	(IR)	Dissolution	Ca/P	HP/P
Aluminum*	(-)	(-)	(+)	(-)	(+)
Magnesium*	(-)	(-)	(+)	(-)	(+)
Strontium*	(-)	(-)	(+)	(-)	(+)
Zinc*	(-)	(-)	(+)	(-)	(+)
M with F	(+)	(+)	(-)	(+)	(-)
Fluoride alone	(+)	(+)	(-)	(+)	(-)

*, without F; (-) decrease; (+) increase (±) increase/decrease, depending on level (Fig. 7).

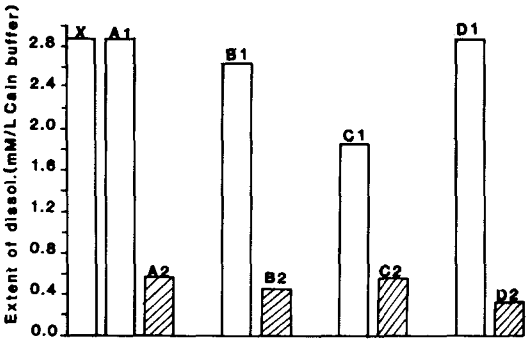

Fig. 7. Extent of dissolution of apatites obtained from solutions containing aluminum, with Al/Ca= 0/1(X); 0.01/1 (A); 0.02/1 (B); 0.03/1 (C) and 0.08/1 (D); without F (A1,B1,C1,D1) and with F (A2,B2,C2,D2), solution F/P=0.2/1. (Dissolution in acetate buffer 0.1 mol/L KAc, pH 5, 37°C, 30 min suspension of apatite powder in the acid buffer.

Fluoride-cation interactions

(a) **Incorporation of the cations in the apatite** The simultaneous presence of F^- ions with the cations (Mg^{2+}, Sr^{2+} and Zn^{2+}) allowed a greater incorporation of these ions in the apatite as shown in Fig. 8. The calculated M*/Ca in the apatite increased in solutions also containing F^-, the increase was greater at higher M* concentrations, e.g., Zn/Ca = 0.03/1 compared to 0.01/1 (Figs. 8B2 compared to 8A2); Mg/Ca = 0.03/1 compared to 0.01/1 (Figs. 8D2 vs 8C2).

(b) **Effect of cations on the incorporation of F in the apatite** Within the concentration levels of this study (M*/Ca = 0.01/1 and 0.03/1; (Ca) = 10 mM/L), no significant effect on the incorporation of F in the apatite was observed.

(c) **Effect of the simultaneous presence of F^- ions in solution on the formation of Mg-substituted β-TCP** When Mg^{2+} concentration in solution is 0.05/1 (Mg/Ca, (Ca) = 10 mM/L), Mg-substituted whitlockite, β-TCP formed at the expense of apatite. As reported previously, Mg^{2+} stabilized the whitlockite or β-TCP which normally does not form from aqueous solution [17,21,22,30,46].

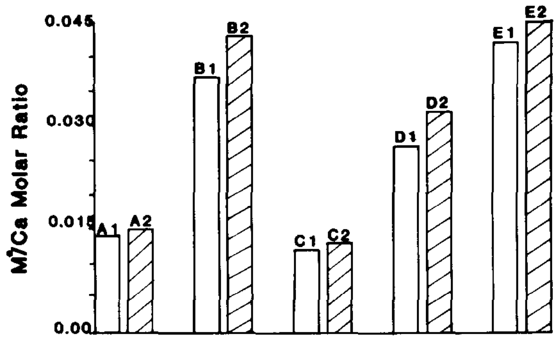

Fig.8. Effect of solution F^- on the incorporation of some cations: zinc (A2,B2); magnesium (C2,D2); and strontium (E2). The extent of incorporation of these cations in the apatite obtained were greater when F^- ions are simultaneously present with the cation in the solution. Without F: A1,B1,C1,D1,E1; with F: A2,B2,C2,D2,E2. Zn/Ca in solution=0.01/1(A); 0.03/1(B); Mg/Ca=0.01/1(C); 0.03/1(D); Sr/Ca=0.05/1(E).

However, when F^- was simultaneously present with Mg^{2+} in the solution, F-substituted apatite was formed preferentially, suppressing the formation of Mg-substituted β-TCP(Fig.9B,Mg/Ca=0.08/1,F absent,the principal product was Mg-substituted β-TCP;Fig.9D,F present with Mg,product was F-substituted apatite.

(d) Effects of the simultaneous presence of F^- ions with other cations (Al^{3+}, Mg^{2+}, Sr^{2+}, Zn^{2+}) in solution on the properties of apatites formed. The negative effects of the cations on the properties of the apatites were greatly minimized when F^- ions were simultaneously present (Table 1;Figs.2,3,4,6 and 7)

CONCLUSION

Fluoride ions present in the media causes the formation of F-containing apatites which are more resistant to acid dissolution than F-free apatites. The negative effects of other cations (aluminum, magnesium, strontium or zinc) on the properties of the apatites are minimized and even nullified by the simultaneous presence of fluoride. Fluoride promotes the formation of synthetic or biological (e.g., enamel, dentin or bone mineral) apatites which are structurally and chemically more stable than F-free apatites.

ACKNOWLEDGEMENTS

The valuable technical assistance of Wilma Torres, David LeGeros and Xia-Fei Chang, the support of the National Institutes of Health (NIDR) Research Grant Nos. DE-04123 and DE-07223 are gratefully acknowledged. The assistance of G. Marlino (photography) and Beth Yurchak (word processing) are also gratefully acknowledged.

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