

Coprecipitation of Copper with Hydroxyapatite

Tsunenobu SHIGEMATSU, Osamu FUJINO and Masakazu MATSUI*

Received October 17, 1972

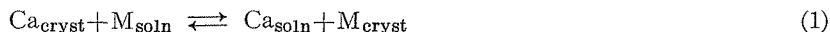
The distribution behavior of cupric ion between aqueous phase and hydroxyapatite crystal was investigated. The apatite prepared by adding phosphate ion extremely slowly in calcium solution at 80°C, yielded a X-ray diffraction pattern of hydroxyapatite and had a composition that Ca/P molar ratio was 1.67 at pH 6.80. Apparently, the coprecipitation reaction seems to be anomalous, because the apparent distribution coefficient did not have a constant value through the reaction. But when true distribution coefficient was calculated, it was revealed that cupric ion was coprecipitated obeying logarithmic distribution law. Cupric ion seems to be somewhat unstable in the apatite crystal, judging from the influence of copper concentration.

INTRODUCTION

Many radioisotopes ingested into human body are deposited in mineral bone. Although it is known that the bone mineral is not a single, homogeneous chemical substance, there is evidence from its chemical composition and X-ray diffraction analysis that it is basically hexagonal hydroxyapatite, *i. e.*, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$. A number of substitutions are possible in the apatite; for instance, such ions as strontium, radium and lead can be substituted for the divalent cation, calcium.¹⁾

Apatite is also geochemically a very interesting mineral. According to Krauskopf,²⁾ apatite is an effective coprecipitant from sea water for certain trace elements, particularly elements such as the rare earths which have very insoluble phosphates.

When a substance is precipitated very slowly, foreign ion in a solution phase distributes themselves systematically between the solid and solution phases. For a system in which calcium ion has been precipitated to form hydroxyapatite in the presence of a foreign divalent metal ion, the reaction is:



The equilibrium constant, *i. e.*, thermodynamic distribution coefficient, K_M , for this system is:

$$K_M = \frac{a_{\text{Ca}}^{\text{soln}} \cdot a_{\text{MPh}}^{\text{cryst}}}{a_{\text{M}}^{\text{soln}} \cdot a_{\text{CaPh}}^{\text{cryst}}} = \frac{S_{\text{CaPh}}}{S_{\text{MPh}}} \quad (2)$$

$$= \frac{m_{\text{Ca}} \cdot \gamma_{\text{Ca}}^{\text{soln}} \cdot m_{\text{MPh}}^{\text{cryst}} \cdot \gamma_{\text{MPh}}^{\text{cryst}}}{m_{\text{M}} \cdot \gamma_{\text{M}}^{\text{soln}} \cdot m_{\text{CaPh}}^{\text{cryst}} \cdot \gamma_{\text{CaPh}}^{\text{cryst}}} \quad (3)$$

where S_{CaPh} and S_{MPh} are the solubility products of calcium and divalent metal apatites, and a^{cryst} and a^{soln} designate the activities of the chemical species in the crystal and solution phases, respectively. m_{CaPh} and m_{MPh} are the mole fractions of calcium and divalent

* 重松 恒信, 藤野 治, 松井 正和: Laboratory of Radiochemistry, Institute for Chemical Research, Kyoto University, Uji, Kyoto.

metal in the apatite crystals; m_{Ca} and m_M are the molar concentration of calcium and metal ions in the solution phase. γ_{CaPh}^{cryst} and γ_{MPh}^{cryst} denote the activity coefficients in the crystals of calcium and metal phosphates; γ_{Ca}^{soln} and γ_M^{soln} denote those in the solutions of calcium and metal ions.

The apparent distribution coefficient, K'_M , is defined:^{3,4)}

$$K'_M = \frac{C_{Ca} \cdot m_{MPh}}{C_M \cdot m_{CaPh}} \quad (4)$$

where C_{Ca} and C_M are the total concentrations of calcium and metal ions in the solution phase. This is called homogeneous distribution law.

If the distribution equilibrium is attained between the crystal surface and the solution phase, the logarithmic distribution coefficient is expressed as follows:⁵⁾

$$K'_M = \log \frac{C_{M, initial}}{C_{M, final}} / \log \frac{C_{Ca, initial}}{C_{Ca, final}} \quad (5)$$

When there exist complex-forming ions in the solution phase, total ion concentrations of calcium, metal and ligand are given by:

$$C_{Ca} = m_{Ca} \{1 + \sum \beta_i^{CaLi} m_L^i\} \quad (6)$$

$$C_M = m_M \{1 + \sum \beta_i^{MLi} m_L^i\} \quad (7)$$

$$C_L = m_L \{1 + \sum \beta_i^{LH_{n-i}} [H]^i\} + m_{Ca} \sum \beta_i^{CaLi} m_L^i + m_M \sum \beta_i^{MLi} m_L^i \quad (8)$$

where m_L is the molar concentration of ligand, and $\beta_i^{LH_{n-i}}$, β_i^{CaLi} and β_i^{MLi} denote the cumulative or gross stability constants of proton, calcium and metal complexes with the ligand, respectively. The distribution coefficient, K_M , for the reaction of Eq. 1, is calculated from Eqs. 2–8, assuming that all activity coefficients are equal to unity.

The distribution described above can be considered as a fundamental phenomenon in distributing metal ions into apatite. Previously, coprecipitation behaviors of strontium, zinc, cadmium and rare earths were investigated.⁶⁾ In this paper, we dealt with the coprecipitation behavior of cupric ion which distributes widely in natural water system, with hydroxyapatite.

EXPERIMENTAL

Apparatus and Reagents

Spectrophotometric measurements were made with a Hitachi Perkin-Elmer 139 UV-VIS spectrophotometer using 1.00 cm cells, and for the pH measurements, a Hitachi-Horiba pH meter, model F-5 was used.

Calcium solution was prepared from reagent grade nitrate and standardized with EDTA titration. Copper solution was prepared by dissolving copper metal with nitric acid and by diluting with pure water. Standard EDTA solution containing EDTA-magnesium chelate, was standardized with calcium solution which was prepared from dry calcium carbonate.

All the other reagents were reagent-grade materials.

Preparation and Composition of Hydroxyapatite

Five hundred milliliters of aqueous solution which contained calcium nitrate (0.02 M), sodium malonate (0.015 M) and sodium borate (0.01 M), were taken in 1 l Erlenmeyer flask and adjusted to a desired pH value. The flask equipped with a reflux condenser, was placed in a thermostat regulated at 80°C and was passed in nitrogen gas to prevent the carbonate contamination. The phosphate precipitation was prepared by pumping the diammonium hydrogen phosphate (0.10 M) into the calcium solution extremely slowly, being stirred by a magnetic stirrer. After washed with water three times, the precipitate was dried at 110°C for one day. Phosphate ion in the precipitate was determined spectrophotometrically with molybdovanadophosphoric acid method,⁷⁾ and calcium was determined by back-titrating an excess of EDTA added in sample solution with magnesium standard solution (0.005 M).

Coprecipitation Procedure

The coprecipitation procedure was almost the same as that described in the apatite preparation except the addition of cupric ion. At appropriate intervals of time, an aliquot of the supernatant solution was pipetted out. After the centrifugal separation of the solution phase, calcium was determined by EDTA titration method, and cupric ion was determined spectrophotometrically by the carbon tetrachloride extraction method as copper diethyldithiocarbamate.

RESULTS AND DISCUSSION

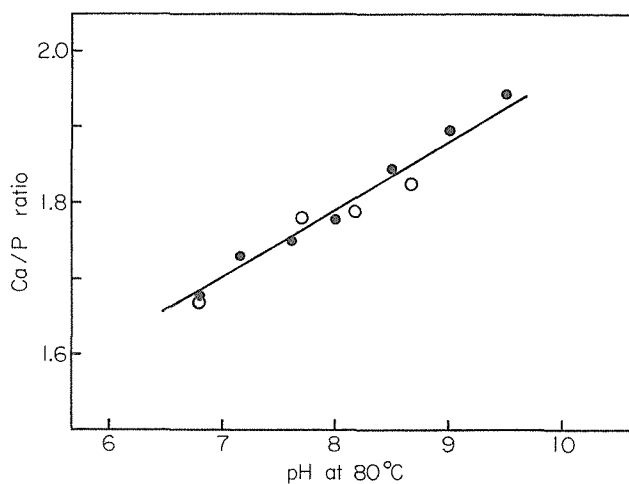
Composition of Hydroxyapatite

Non-stoichiometric apatites have been reported,⁸⁾ though these have X-ray diffraction patterns typical of hydroxyapatite. Previously, the Ca/P molar ratio of the apatites which were precipitated from the solutions buffered by ethylenediamine (0.25 M), was examined in detail.⁶⁾ In this experiment, sodium borate was used instead of ethylenediamine as a buffering agent, because of too much stable chelation of copper with ethylenediamine. And malonate solution (0.015 M) was used as a chelating agent, because the malonate ion made its copper chelate with a moderate stability.

The effect of the pH on the Ca/P molar ratio of the apatites which were prepared by precipitating 50 per cent of calcium with phosphate solution, was shown in Fig. 1. This indicates that the molar ratio of this system is almost the same as that of ethylenediamine solution. The Ca/P ratio of the apatite synthesized at pH 6.80 was 1.67. This precipitate corresponded to the hydroxyapatite, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ and showed the typical X-ray pattern of hydroxyapatite.

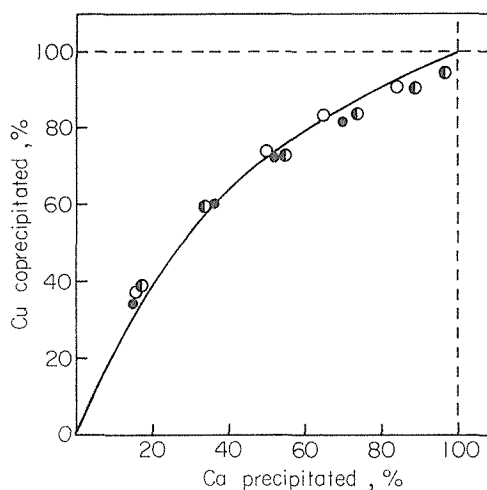
The Effect of the Precipitation Rate on Copper Coprecipitation

In order to check the influence of the dropping rate of phosphate solution on copper coprecipitation, the precipitation reaction was performed at the pumping velocity of 6.0, 10.5 and 31.5 ml of phosphate solution per hour, and at pH 6.80 and 80°C; the concentration of calcium, copper and malonate were 2×10^{-2} , 3×10^{-5} and 1.5×10^{-2} M, respectively. As shown in Fig. 2, where the percentages of coprecipitated copper were plotted against the precipitation percentages of calcium, the effect of precipitation rate was not observed.



●: 0.01 M of borate, ○: 0.25 M of ethylenediamine,
Ca: 0.02 M, dropping rate of phosphate: 10 ml/hr.

Fig. 1. The effect of pH on Ca/P ratio.



●: 6.0 ml/hr. of 0.1 M hydrogenphosphate,
○: 10.5 ml/hr., ◐: 31.5 ml/hr.,
sodium malonate: 1.5×10^{-2} M, Cu: 3×10^{-5} M,
Ca: 0.02 M, pH: 6.80, temperature: 80°C

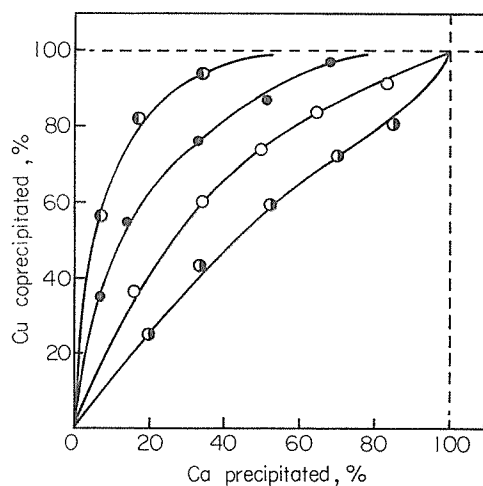
Fig. 2. The effect of precipitation rate.

The Effect of Malonate Concentration

The effect of malonate concentration was examined with the solutions containing 5.0×10^{-3} , 1.0×10^{-2} , 1.5×10^{-2} and 2.0×10^{-2} M of malonate. The results obtained at pH 6.80 were shown in Fig. 3, where the coprecipitation of copper rather increased as the malonate concentration decreased. The apparent distribution coefficients were calculated

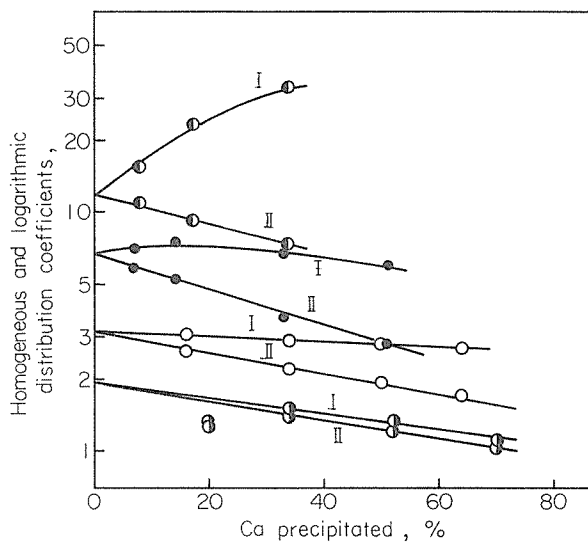
Coprecipitation of Copper with Hydroxyapatite

from these data and by using Eqs. 3 and 4, and were plotted against the precipitation percentages of calcium as shown in Fig. 4.



The total concentration of malonate,
 ○: 5.0×10^{-3} M, ●: 1.0×10^{-2} M, ○: 1.5×10^{-2} M,
 ○: 2.0×10^{-2} M, Ca: 0.02 M, Cu: 3×10^{-5} M,
 dropping rate of phosphate: 10.5 ml/hr., pH: 6.80

Fig. 3. The effect of malonate concentration.



I: logarithmic distribution coefficient,
 II: homogeneous distribution coefficient,
 malonate concentration;
 ○: 5.0×10^{-3} M, ●: 1.0×10^{-2} M,
 ○: 1.5×10^{-2} M, ○: 2.0×10^{-2} M

Fig. 4. The apparent distribution coefficients through the coprecipitation process of copper.

The coprecipitation process appeared to be an anomalous system. Namely, in Fig. 4 cupric ion was coprecipitated by the apatite without obeying any distribution law described above; the apparent distribution coefficients of copper did not show a constant value through a coprecipitation process. This phenomenon was caused by the fact that the malonate ion was released from the calcium malonate as the precipitation reaction proceeded. The increase of the uncomplexed malonate ion was not so small that the second term of Eq. 8 could not be neglected when the true distribution coefficient was calculated by Eqs. 2-8.

True and apparent distribution coefficients, K_{Cu} and K'_{Cu} , were shown in Table 1, where cupric ion was coprecipitated obeying logarithmic distribution law: the true distribution coefficient had a constant value, about 2,200. But this true distribution coefficient may have some error because this was calculated from the thermodynamic data at 25°C.

Table 1 Apparent and True Distribution Coefficients of Copper

Total malonate, M	Ca precipitated, %	Logarithmic coefficient	
		K'	$\log K$
5×10^{-3}	7.29	10.87	3.40
	16.89	9.47	3.39
	33.58	7.05	3.34
1×10^{-2}	7.16	5.84	3.39
	13.91	5.25	3.39
	32.90	3.67	3.32
1.5×10^{-2}	16.11	2.65	3.25
	34.62	2.20	3.22

C_{Cu} : 3×10^{-5} M, C_{Ca} : 2×10^{-2} M, pH: 6.80, Temperature: 80°C.

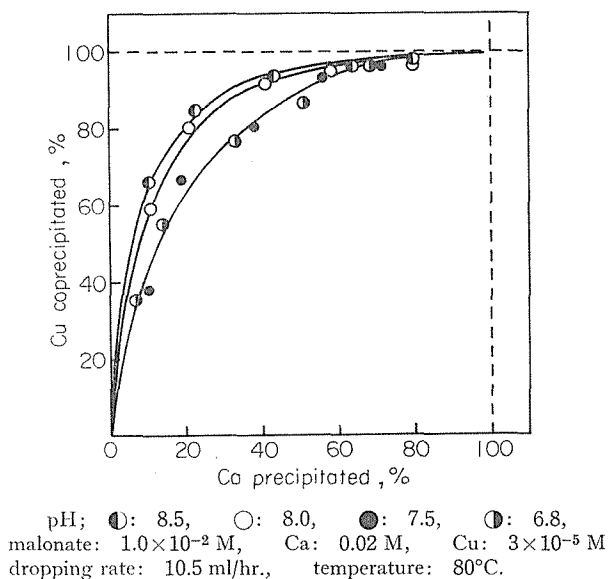


Fig. 5. The effect of pH on copper coprecipitation.

The Effect of pH

The effect of the pH value on the coprecipitation was examined. The results were shown in Fig. 5, in which the percentages of coprecipitated copper at 6.8, 7.5, 8.0 and 8.5 of pH values were plotted against the fractions of calcium precipitated. The apparent limiting distribution coefficient which was extrapolated to zero per cent of precipitated calcium, was plotted against the pH in Fig. 6. These diagrams show that the extent of copper coprecipitation increased as the pH value rised. As the proton-ligand stability constants of malonic acid are 5.67 for K_1 and 2.85 for K_{12} at 25°C, there exists mainly divalent malonate anion in the pH range investigated. Therefore, the change by the pH value was caused not by the increase of malonate concentration, but probably by the variation of apatite composition.

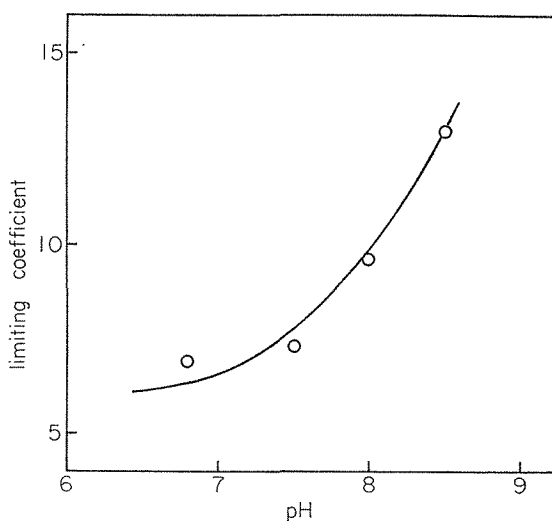


Fig. 6. The apparent limiting distribution coefficient on several pH values.

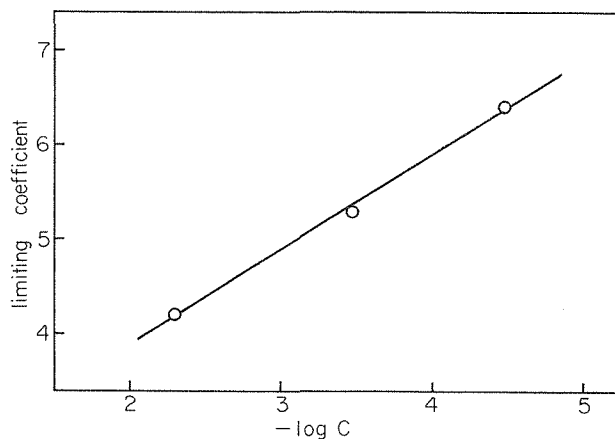


Fig. 7. The effect of copper concentration.

The Effect of Copper Concentration

The hydroxyapatite was precipitated in the solutions containing 5×10^{-3} , 3×10^{-4} and 3×10^{-5} M of copper, respectively. The effect of the copper concentration was indicated in Fig. 7. The limiting distribution coefficient was somewhat influenced by the copper content in the concentration range investigated. This means that it is considerably difficult for the cupric ion to form a solid solution in the calcium apatite crystal.

ACKNOWLEDGMENT

The authors would like to express their thanks to Prof. E. Suito of Kyoto University for his helpful discussions and Mr. T. Yoshida of Kyoto University for X-ray measurements.

REFERENCES

- (1) F. W. Spiers, "Radioisotopes in the Human Body", Academic Press, New York, (1968), p. 131.
- (2) K. B. Krauskopf, *Geochim. Cosmochim. Acta*, **9**, 1 (1956).
- (3) W. Chlopin, *Z. anorg. u. allgem. Chem.*, **143**, 97 (1925).
- (4) L. M. Henderson and F. C. Kracek, *J. Amer. Chem. Soc.*, **49**, 738 (1927).
- (5) H. A. Doerner and W. M. Hoskins, *ibid.*, **47**, 662 (1925).
- (6) T. Shigematsu *et al.*, to be published.
- (7) D. F. Boltz, "Colorimetric Determination of Nonmetals", Interscience New York, (1958), p. 36.
- (8) A. S. Posner, "Phosphorus and its Compounds", Interscience, New York, (1958), Vol. II, p. 1429.