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Study of the influence of inorganic and organic additives on the possibility and regularity of the precipitation process of brushite from aqueous solutions

The article presents a range of issues related to the peculiarities of brushite crystallization in the presence of additives based on thermodynamic calculations and experimental data. The authors studied the regularities of phase formation in the system of Ca^{2+} – HPO_4^{2-} – H_2O, an additive in a broad range of variation of concentrations of components and pH. The effect of silicate-, fluoride-, chloride- and hydrocarbonate-ions on the precipitation and the composition of the crystallizing phase was investigated. It was found that brushite and other calcium phosphates co-precipitate from the original system. Studying the influence of organic additives, it has been established that their presence leads to the precipitation of brushite admixed with apatite phase.

Key words: Brushite, thermodynamic calculations, experimental data, silicate-, fluoride-, chloride- hydrocarbonate-ions, crystallizing phase, calcium phosphates, organic additives, apatite phase.

Introduction

In recent years, considerable attention has been paid to the creation of ceramic materials for medical purposes used in reconstruction of bone tissue defects caused by pathological changes in the body, major surgical interferences or trauma. The use of the materials on the basis of calcium phosphates provides unique opportunities, since this group of compounds is characterized by biological compatibility with body tissues, active combination with bone tissue and the formation of new bone tissue. These properties are widely used for the production of artificial bone grafts, which are either entirely made or only surface-coated with biocompatible calcium phosphates. For example, self-hardening cements of calcium orthophosphates are used in bone regeneration, while titanium prostheses coated with a surface layer of calcium orthophosphate are used for endoprosthesis replacement of hip joints and teeth. Porous support structures made of calcium orthophosphates are promising tools in tissue engineering [1–5].

Another reason giving rise to a great deal of interest in studies of these minerals is the fact that apatite is the main part of the inorganic physiogenic (bones, teeth) and pathological (i.e., those appearing due to various diseases) hard tissues. For example, dental caries and osteoporosis occur due to the partial removal of calciferous matter (decalcification) of teeth and bones respectively. This is a consequence of substitution of less soluble and more solid biological apatite with more soluble and soft dicalcium phosphate. Therefore, the processes of both physiogenic and pathological crystallization in vivo are crystallization of calcium phosphate.

This paper deals with brushite — dihydrate dicalcium phosphate $CaHPO_4 \cdot 2H_2O$ (dicalcium phosphate dihydrate — DCPD) which is a quite common but as yet poorly studied biologically important mineral.

DCPD is of frequent occurrence in the composition of pathogenic mineral formations such as dental stones, kidney stones [6–10]. In medicine it is used in cement compositions based on calcium phosphate. DCPD is included in cavity protection toothpastes (in this case it is present together with the fluorine-containing compounds) and is a mild polishing agent [2, 5, 11].

Analysis of the literature [1, 5, 12] shows that the crystallization process of brushite in a greater degree depends on the parameters of the solution (such as initial concentration of the components, the pH of the medium) and the reaction conditions (temperature, time of solid phase crystallization, the rate of solution pouring, the mixing procedure). Since the conditions under which brushite is formed are very diverse, the selection and specification of synthesis parameters of this phase from aqueous solutions are urgent and complex problems of modern science. In addition, the research aimed at studying the nature of the influence of inorganic and organic additives (components of biological fluids of the human body) on the properties of the synthetic solid phase is very important.

The aim of this work is to study the effect of organic and inorganic additives on the opportunity and the regularities of the precipitation process of brushite from aqueous solutions.

Materials and methods

Thermodynamic calculation. At the initial stage of the study, thermodynamic calculation was conducted to determine the feasibility and conditions of precipitation of slightly soluble calcium compounds. Aqueous solutions containing ions of calcium, phosphate, nitrate ions and ammonium were chosen as the systems to study the regularities of crystallization. The concentration of calcium and phosphate ions was varied between 10 and 200 mmol/L, the content of counter-ions in the system corresponded to the equilibrium stoichiometric concentration after dissociating of calcium nitrate and ammonium hydrophosphate in aqueous medium. The consideration of these ions was reduced to the description of their impact on the non-ideality of the solution due to the electrostatic interactions of ions constituents related to the ionic strength of the solution. The calculation of activity ratio of ions was carried out according to the equation of the second approximation of the Debye-Huckel theory [13].

During calculations, the value of acidity ranged from 0 to 14, with a step increment of 0.1. Stepped hydrolysis of phosphate ions in the solution was considered by the introduction of the value of mole fractions of those anion forms that are a part of a slightly soluble composition, in the equation for relative solubility products. According to the existing data [3–5, 11, 12], in aqueous solutions containing calcium ions and phosphate ions, the following slightly soluble compounds are formed: $Ca(H_2PO_4)_2 \cdot H_2O$ (monocalcium phosphate monohydrate), $Ca(H_2PO_4)_2$ (monocalcium phosphate), $CaHPO_4 \cdot 2H_2O$ (brushite), $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ (octacalcium phosphate, OCP), $Ca_{10}(PO_4)_6(OH)_2$ (hydroxyapatite, HA), β-$Ca_3(PO_4)_2$ (tricalcium phosphate, TCP), $Ca(OH)_2$. To determine the feasibility and the conditions of the precipitation of the listed substances, we used the values of thermodynamic solubility products (pK^o_s) corresponding to the instability constants data base of complexes SC-database [SCQUERY Version 1.37 (1993)]. Theoretical determination of feasibility and conditions of precipitation of these slightly soluble calcium compounds in aqueous media was carried out based on calculations of thermodynamic parameters characterizing the degree of the system deviation from equilibrium. The value of supersaturation index (SI) of the system for each of the compounds was calculated according to [14]. The driving force of the crystallization process was characterized by the change in Gibbs' free energy (ΔG) when the system transfers from a supersaturated state to equilibrium [14].

If $SI > 0$, $\Delta G < 0$ and precipitation of the solid phase from the solution is thermodynamically probable.

Experimental modeling. Brushite crystals were obtained by mixing the dilute solutions of calcium nitrate and ammonium hydrogen phosphate as a result of the precipitation reaction:

$$Ca(NO_3)_2 + (NH_4)_2HPO_4 + 2H_2O \rightarrow CaHPO_4 \cdot 2H_2O\downarrow + 2NH_4NO_3$$

The study of the system was carried out at the equimolar concentrations of the solution of $Ca(NO_3)_2$ and $(NH_4)_2HPO_4$ at room temperature (22–25 ºC). During the experiment, the concentration of additives was varied.

The solution was filtered under vacuum after sedimentation of the heterogeneous system during the chosen period of time. The precipitate was dried at a temperature of ~80 ºC to the constant weight for complete removal of the chemically not-bound water. The obtained solid phase was weighed and studied by the methods of X-ray diffraction analysis (XRD) (DRON-3M), by Fourier-transform infrared spectroscopy (FTIR spectrometer FT-801, tablets with KBr) and optical microscopy.

The analysis of variance was performed on the laser diffraction particle size analyzer ShimadzuSALD-2101 (Laser Diffraction Particle Size Analyzer). According to the results of analysis, we obtained a curve of particle size distribution and average particle size in microns using special software (WING-2; WING-3). For more reliable results, the analysis of the samples was carried out in 4–5-fold repetition, and the relative standard deviation for these measurements was Sr = 0.02–0.04.

The statistical data processing was carried out using software StatSoft Statistica 6.0.

Results and their discussion

Thermodynamic modeling. The comparison of the values of solubility products $K_s^{/}$ of studied slightly soluble compounds, calculated taking into account the ionic strength and hydrolysis processes, with values of thermodynamic constants $K_s°$ showed that in all systems in which $C_{Ca(NO_3)_2} / C_{(NH_4)_2HPO_4} = 1.33–2.00$, crystallization is thermodynamically possible $CaHPO_4 \cdot 2H_2O$; $Ca_{10}(PO_4)_6(OH)_2$; $Ca_8H_2(PO_4)_6 \cdot 5H_2O$, β-$Ca_3(PO_4)_2$ and $Ca(OH)_2$ (for them $K_s^{/} > K_s°$). By increasing the ratio of concentrations of calcium and phosphate ions in the solution, the change of composition and the number of phases (with respect to which the medium is in a supersaturated state) is not observed. The conditions, under which the deposition of a particular solid phase is possible, are virtually unchanged at varying initial concentrations of the ions forming the precipitation. So

the diagrams of crystallization of all of the slightly soluble calcium orthophosphates, for which precipitation is possible in the studied systems, are almost invariant with the changes of the parameter Ca/P in the solution (Fig. 1). Consequently, the magnitude $C_{Ca(NO_3)_2} / C_{(NH_4)_2HPO_4}$ (when changing from 1.33 to 2.00) does not have a significant influence on the conditions and sequence of crystallization of slightly soluble compounds of calcium.

Acidity of the medium has the greatest influence on the process and depth of the reaction behavior of precipitation. The stability region of $Ca_{10}(PO_4)_6(OH)_2$ ($SI > 0$) is significantly expanded by increasing the pH value, reaching a maximum at pH = 12 (Fig. 1), whereupon the supersaturation is virtually unchanged and remains constant (SI = 3.70). A similar trend is observed for β-$Ca_3(PO_4)_2$ (Fig. 1).

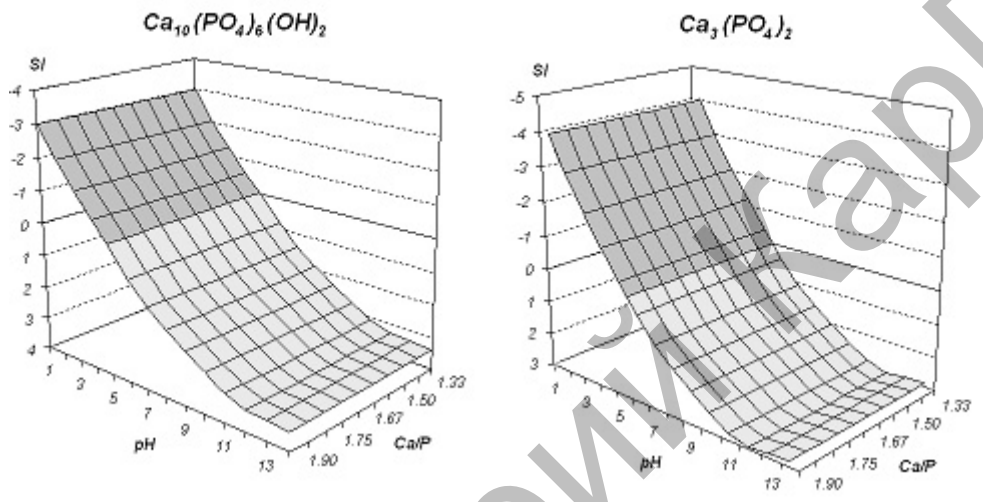


Figure 1. Diagrams of crystallization of calcium orthophosphates ($Ca(NO_3)_2$ / $(NH_4)_2HPO_4$ = 1.67)

The established regularity is due to the fact that with increasing pH value, the mole fraction of orthophosphate ions in the system increases, and at pH>12, the form PO_4^{3-} predominates in the solution, as the phosphorus in the form of trisodium orthophosphate ion is included in the composition of $Ca_{10}(PO_4)_6(OH)_2$ and β-$Ca_3(PO_4)_2$. The supersaturation of the solution concerning the calcium orthophosphates increases, as the pH increases with that the field of their existence expands, the rate and depth of deposition of the reaction increase [14].

It is known that $CaHPO_4 \cdot 2H_2O$ and $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ phases that crystallize in slightly acidic and close to neutral solutions. The areas obtained in the calculations of the possible deposition of the mentioned salts have the boundaries of 5.0–13.7 and 5.7–14, respectively for $CaHPO_4 \cdot 2H_2O$ and $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ (Fig. 1). In practice, in aqueous solutions at pH close to 7, the processes of hydrolysis of the considered calcium orthophosphates with the formation of thermodynamically more stable $Ca_{10}(PO_4)_6(OH)_2$ start. Probably, this is due to the lack of experimental data regarding the availability of $CaHPO_4 \cdot 2H_2O$ and $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ in aqueous alkaline solutions and their stable existence in time. However, according to [12], the range of pH medium of crystallization at the nonequilibrium growth of brushite (in gel media) is significantly wider than the well-known thermodynamic equilibrium range 4<pH<6 and includes all experimentally studied pH range from 3 to 8 [12].

In the transition from dilute solutions to the systems with a higher concentration, a significant decrease in the Gibbs energy of the crystallization process of $Ca_{10}(PO_4)_6(OH)_2$, $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ and β-$Ca_3(PO_4)_2$ is observed [14]. This change reaches 4–6.5 kJ/mol when the concentration of calcium ions and phosphate ions increases in the system by 20 times. The driving force of the deposition process of brushite varies slightly depending on the concentration of precipitation forming ions in the medium and reaches its maximum value (–6.78 kJ/mol) at concentrations = 50–75 mmol/l.

According to the thermodynamic calculations, it is established that in the systems with the concentrations of phosphate ions and calcium ions of 10 to 200 mmol/l and pH from 0 to 14, the deposition of two of calcium phosphates is most likely: at pH ~ 4.7–6.0 and C≥50 mmol/l — brushite, at pH>6.0 and C<50 mmol/l — apatite, $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ and β-$Ca_3(PO_4)_2$ metastable phases in the studied conditions.

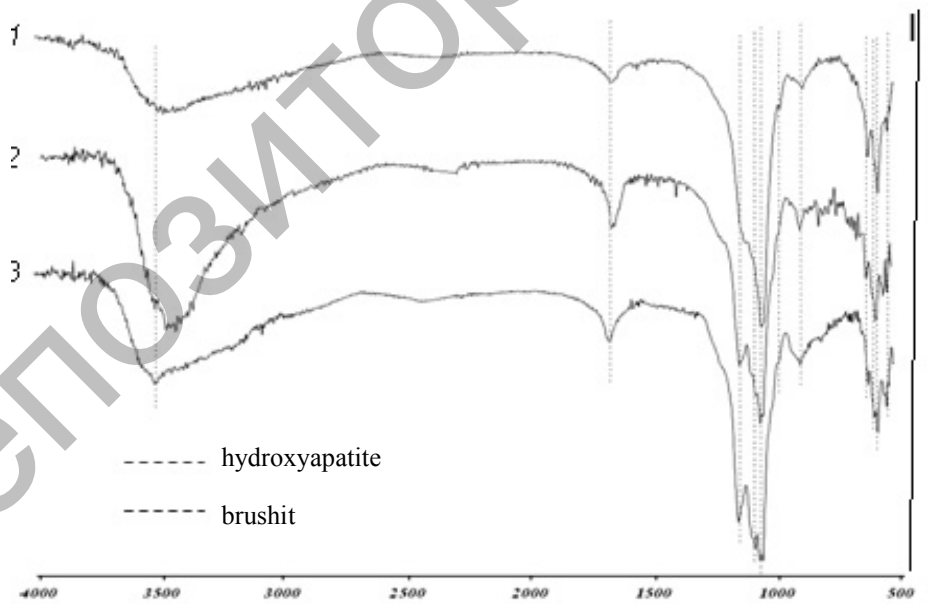
The theoretical results are confirmed during the experimental study of the system of $Ca(NO_3)_2$–$(NH_4)_2HPO_4$–H_2O, containing equivalent amounts of ions of Ca^{2+} and HPO_4^{2-}: at low concentrations (10–50 mmol/l) at the time of pouring of solution the brushite crystallizes, which as it matures in the system, transformes into hydroxyapatite; at higher contents of ions of Ca^{2+} and HPO_4^{2-} in the systems (≥50 mmol/l) brushite deposits, the size of the crystals of brushite increases during ripening in the solution. The crystallization of brushite takes place in the pH range = 5.00–6.00 at adding a solution of $Ca(NO_3)_2$ to the solution of $(NH_4)_2HPO_4$. The particle size decreases with the decrease of the rate of pouring of the reactants.

It should be noted that the constructed thermodynamic model reflects the possibility of the formation of phases only on the basis of the data about their thermodynamic stability in the standard state. It does not take into account kinetic factors influencing the formation process of the solid phase in the actual conditions.

The concentration of precipitation-forming ions is one of the most important parameters influencing the crystallization process, its direction, velocity, nature and properties of the developing slightly soluble compound. At initially low concentrations of Ca^{2+} and HPO_4^{2-} in the calcium phosphate system, according to the data obtained in the thermodynamic calculations, apatite deposition is possible, whereas, with the increase of the initial concentrations of precipitation-forming ions the supersaturation system increases relative to $CaHPO_4 \cdot 2H_2O$, β-$Ca_3(PO_4)_2$ and $Ca_8H_2(PO_4)_6 \cdot 5H_2O$ and the formation of a mixture of phosphates is thermodynamically probable. Theoretically established regularities were tested in the experiment.

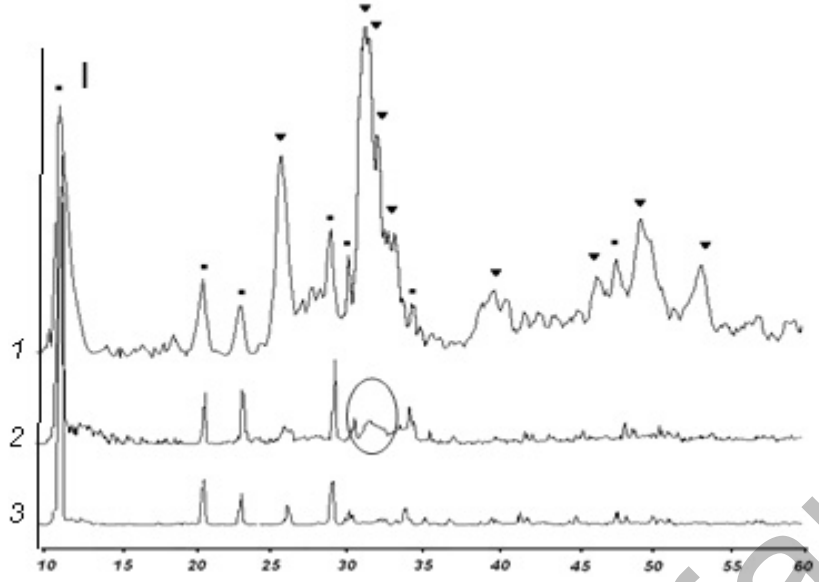
With the methods of XRD, IR-spectroscopy and optical microscopy, it was determined that at the initial time (when pouring reagents) from the solutions with the concentrations of 10 and 25 mmol/l, brushite crystallizes. When the precipitation matures in the mother liquor, small rhombic crystals of brushite mostly transform into apatite; this indicates greater stability of the precipitation in the studied conditions and agrees with the data of thermodynamic calculation. The powders obtained after separation from the aqueous phase and drying are biphasic and consist of brushite and HA (Fig. 2, 3).

In the system where the original concentrations of precipitation-forming ions is 50 mmol/l, brushite crystallizes with impurity of apatite according to IR-spectroscopy and optical microscopy (Fig. 2, 3). However, on the diffractograms of the solid phase obtained under these conditions, only reflexes $CaHPO_4 \cdot 2H_2O$ appear and peaks $Ca_{10}(PO_4)_6(OH)_2$ are absent. This is probably due to the low content of basic calcium phosphate in the composition of the precipitate (less than 5 % from the weight of the total solid phase).



$C(Ca^{2+}, HPO_4^{2-})_{initial}$: *1* — 10 мМ; *2* — 25 мМ; *3* — 50 мМ

Figure 2. IR Spectra of the samples from the systems



▾ hydroxyapatite ■ brushit

$C(Ca^{2+}, HPO_4^{2-})_{initial}$: *1* — 10 мМ; *2* — 25 мМ; *3* — 50 мМ

Figure 3. Diffractogram of the precipitations from the systems

In the studied systems, crystallization of only brushite phase occurs at higher initial concentrations of calcium ions and phosphate ions (C≥75 mmol/l). At the initial stage of their formation, the particles have the form of thin prolate plates, diverging rays from the center (Fig. 4*a*). Maturing of the sedimentary substance in the mother liquor leads to the separation of crystals and their enlargement. The greatest growth occurs in the direction of one of the axes, so the ratio of the crystal length to the width is approximately 10:1 (characteristic feature of brushite crystals [12]). The average particle size of the brushite obtained by precipitation in the systems with concentration ≥75 mmol/l is 17.5–22.5 μm.

a *b* *c*

a — at the moment of pouring together; *b*, *c* — 2 days after maturation

Figure 4. Image of brushite particles obtained from the solution with $C_{initial}$ = 75 mmol/l

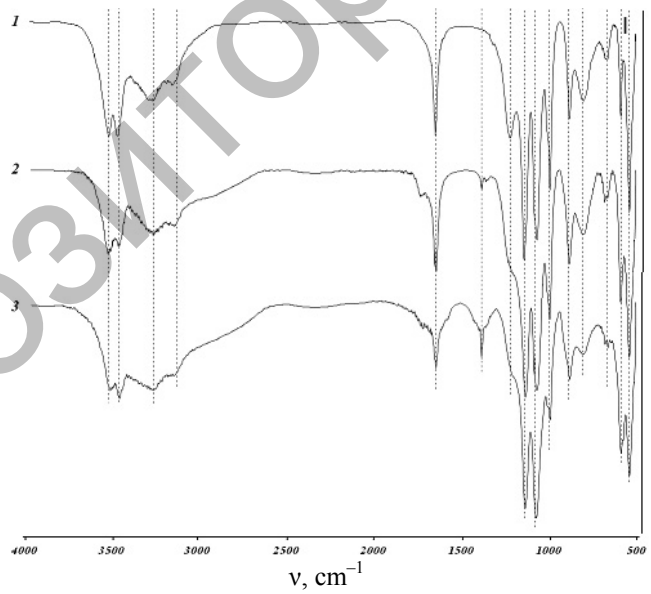
Overall, the results of theoretical and experimental study of the phase formation processes in the system $Ca(NO_3)_2 – (NH_4)_2HPO_4 – H_2O$ agree well with and complement each other. The driving force of the deposition process of brushite was evaluated and the influence of several factors on the regularities of phase formation in the system $Ca(NO_3)_2 – (NH_4)_2HPO_4 – H_2O$ was established. The features of brushite were revealed in the course of comprehensive multicenter study of the spontaneous crystallization of slightly soluble calcium phosphates (controlled by both thermodynamic and kinetic factors). Based on the obtained results it can be stated that further investigation of crystallization of calcium hydrogen phosphate dihydrate in the presence of organic and inorganic substances of biological origin is necessary to clarify the mechanisms of their influence on the processes of mineralization *in vivo.*

Research of the influence of the inorganic anions on the properties of synthetic solid-phase and characteristics of the deposition process

The influence of fluoride ions on the crystallization in the system $Ca(NO_3)_2$ – $(NH_4)_2HPO_4$ – NaF – H_2O. Theoretically, in the given ionic composition (Ca^{2+}, Na^+, NH_4^+, NO_3^-, $H_2PO_4^-/HPO_4^{2-}/PO_4^{3}$, F^-, H^+, OH^-) the deposition of the following slightly soluble calcium compounds is possible $Ca(OH)_2$, $CaHPO_4 \cdot 2H_2O$, $Ca_8H_2(PO_4)_6 \cdot 5H_2O$, $Ca_xH_y(PO_4)_z \cdot nH_2O$, $Ca_{10-x}(HPO_4)_x(PO_4)_{6-x}(OH)_{2-x}$, $Ca_{10}(PO_4)_6(OH)_2$, $Ca_{10}(PO_4)_6F_2$. In the experimental study it was found that in a similar system without the addition of fluoride ions (pH = 5.50 ± 0.05, t = 22–25 ºC, τ = 48 h.) the crystallization of only phase brushite occurs — $CaHPO_4 \cdot 2H_2O$. In the presence of anions F^- in the medium of crystallization, the formation of least soluble phase of all currently known calcium phosphates — fluorapatite is probable. Therefore, the experiment on the crystallization of the solid phase in the presence of fluoride ions, whose content in the system ranged from $1.06 \cdot 10^{-5}$ to $1.06 \cdot 10^{-2}$ mol/l (the minimum concentration corresponds to the content of F^- in human stomatic fluid), was conducted to study the influence of fluoride ions on the process of phase formation in the studied conditions.

The study of the obtained solid phases by IR-spectroscopy showed that the value of the initial concentration of fluoride ions has a significant impact on the nature of the crystallizing substance. With the increase of C_{F^-} in the system, there is a change of the type of crystallization process: brushite → mixture of brushite and hydroxyl/fluoro-apatite → fluorapatite.

The analysis of IR spectra of samples synthesized at higher concentrations of fluoride ions (0.53–1.06 mmol/l) showed that in these conditions the formation of additional crystal phase occurs, probably of fluoro-substituted non-stoichiometric hydroxyapatite $Ca_{10-x}(HPO_4)_x(PO_4)_{6-x}(OH)_{2-2x}F_x$. In this case, the samples are biphasic. The complex structure of the spectrum in the near infrared region (ranges 500–650, 1000–1200 cm^{-1}) proves it. Absorption bands of brushite and apatite are jointly present in this region. With further increase of the initial content of F^- in the system (≥5.30 mmol/l), fluorapatite ($Ca_{10}(PO_4)_6F_2$) is presumably the prevaling component of the obtained precipitate. This is evidenced by the presence of intense peaks at 1040 and 1090 cm^{-1} triply degenerate mode of antisymmetric valence vibration of P–O (ν_3) in the composition of apatite and a broad flat absorption band in the range 3300–3500 cm^{-1} (Fig. 5).



1 — brushite (50mM); *2* — C(F^-) = 53 mM; *3* — C(F^-) = 106 mM

Figure 5. IR spectra of solid phases from the solutions without additives and with the impurity of fluoride ions

The conducted analysis of variance of all obtained solid phases showed that the particle size increases with the increase of initial concentration of the additive of fluoride ions in the initial crystallization medium (Fig. 6). Thus, the precipitations obtained from the solutions with $C_{F^-} \leq 106$ μm have large size

(D_{modal} ~ 50–100 micron) compared to brushite, which precipitation occurred in the medium without additives. The increase of fluorine content in the initial solution leads to a further increase in the particle size of the precipitation. Thus, at C_{F^-} = 1.06 mm, the diameter of particles is about 170 μm.

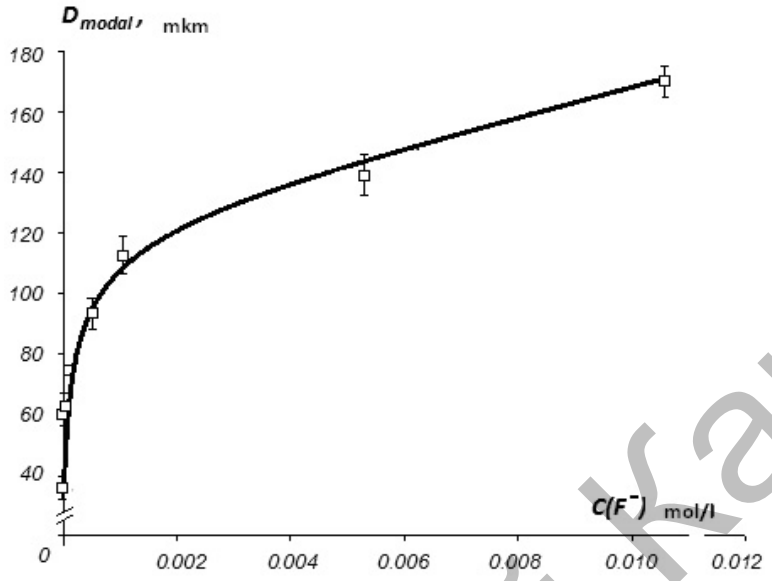


Figure 6. Dependence of the diameter of the particles
on the concentration of the fluoride ions in the system

The presence of one peak on the differential curves of the particle size distribution (Fig. 7, 8) indicates a predominance of particles of certain diameter in the composition of the samples extracted from the solutions with C_{F^-} = 0–1.06 μm. For the samples of fluorapatite obtained at 5.30 μm ≤ C_{F^-} ≤ 10.6 μm, the differential curves have two maxima (Fig. 8); therefore, the solid phase is primarily composed of particles of two fractions, for which $D_{modal(1)}$ = 100–200 μm and $D_{modal(2)}$ = 400–500 μm.

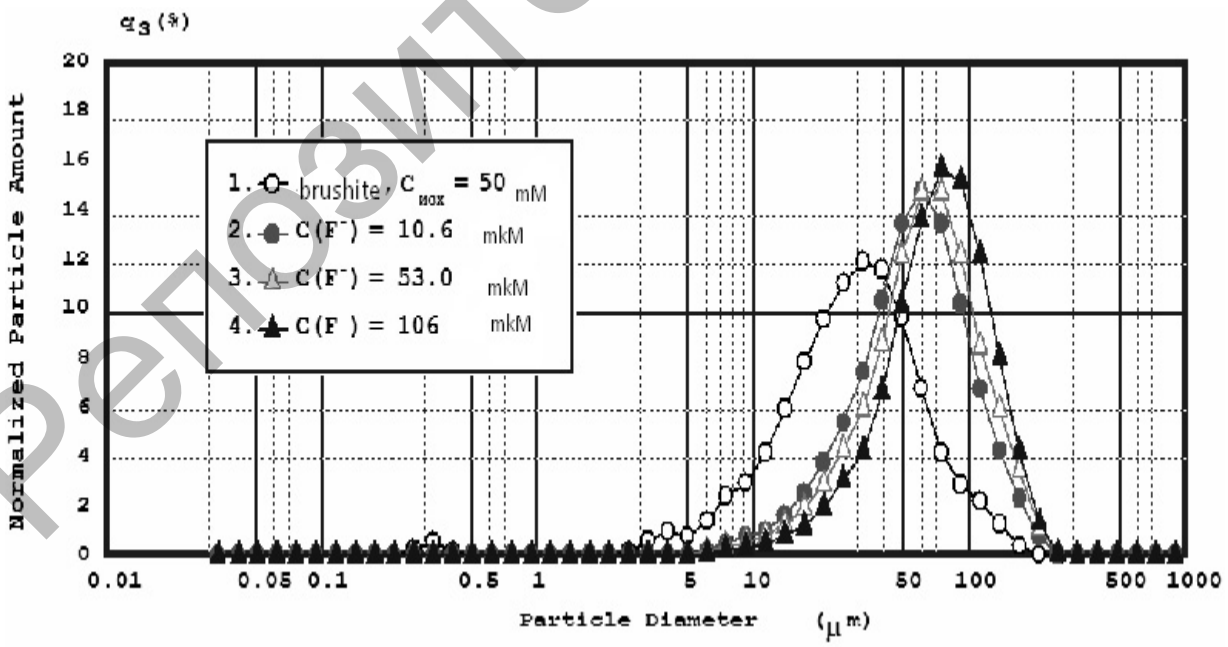


Figure 7. The differential curves of particles size distribution
of the solid phases obtained at C_{F^-} = 10.6–106 mkmol/l, μm

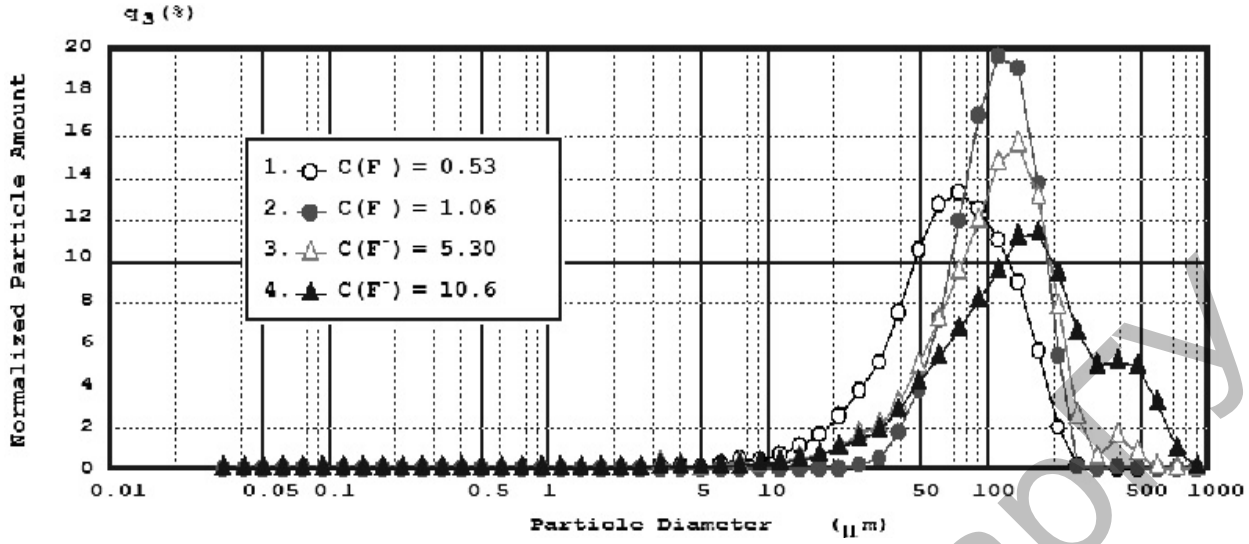


Figure 8. The differential curves of particles size distribution of the solid phases obtained at C_{F^-} = 0.53–6.10 mkmol/l, μm

The influence of chloride ions on the crystallization in the system $Ca(NO_3)_2 – (NH_4)_2HPO_4 – NaCl – H_2O$. The synthesis of brushite conducted in the presence of chloride ions, whose content in the system was varied in the concentration range 0.010–0.100 mol/l (the content of Cl^- in human stomatic fluid — 0.015 mol/L) to study the influence of additives on the process of phase formation under these conditions.

The study of the obtained phases by the method of IR-Fourier spectroscopy enabled to state that Cl^- ions added to the solution even in a small amount of (C(Cl)≥0.010 mol/l) cause joint crystallization of brushite and hydroxyapatite. Thus, on the infra-red spectrum of sample absorption there are peaks at 653, 578 cm^{-1} and also 1135 and 1060 cm^{-1}, which are characteristic for HPO_4^{2-} — groups in brushite, and bands due to variations of water: at 1646 cm^{-1} and a broad band in the region 3500–3000 cm^{-1} with a minimum of 3420 cm^{-1} (Fig. 9).

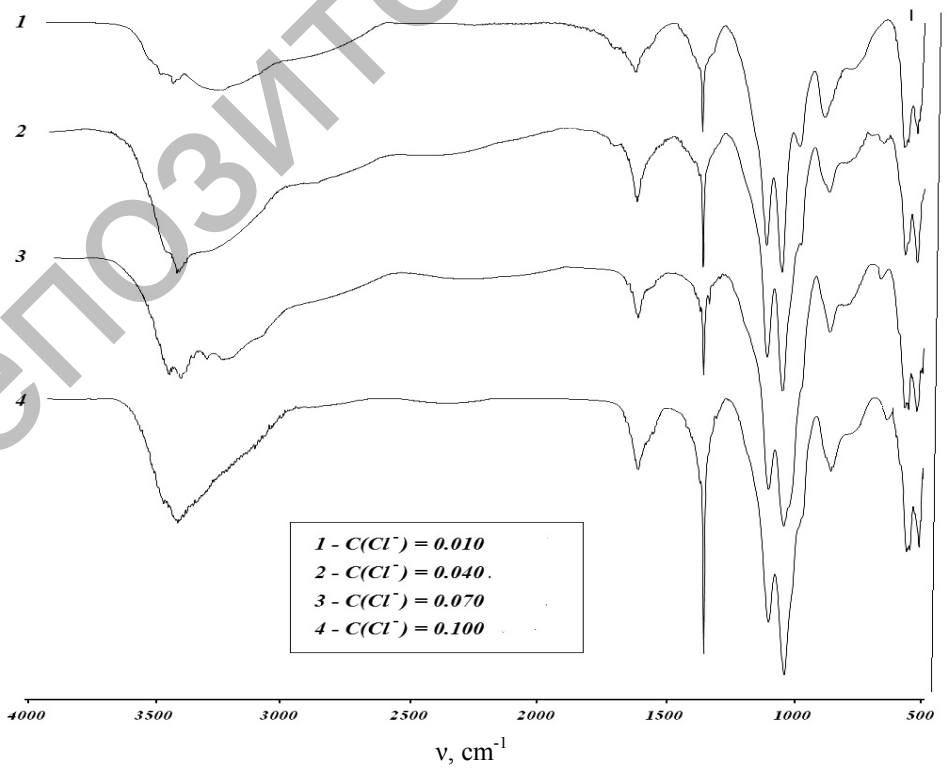


Figure 9. The IR spectra of the synthetic phases in the presence of chloride ions (mol/l)

According to the analysis of variance dispersing composition of synthetic powders the size of the particles of the obtained combinations increases with the concentration of additives in the initial system (see Table). Moreover, for the samples obtained by precipitation from the system with the initial concentration of chloride ions 0.040 and 0.010 mol/l the distribution curves of particle size are bimodal. It indicates the formation of crystals of two fractions (r_{max1} = 30 μm, r_{max1} = 150 μm) (Fig. 10) in the test conditions and shows the presence of two phases in the composition of the precipitation. The dependence with monomodal particle size distribution is characteristic for other synthetic samples, the value of the average diameter of particles ranges from 30 to 70 μm.

Table

Specifications of synthetic solid phases

The concentration of chloride ions in mol/l		Ca/P the precipitate	D, мкм
in the initial solution	solid phase		
0.010	0.002±0.000	1.47±0.04	25.1
0.040	0.002±0.000	1.47±0.04	39.6
0.070	0.005±0.000	1.23±0.13	57.8
0.100	0.008±0.000	1.16±0.04	60.1

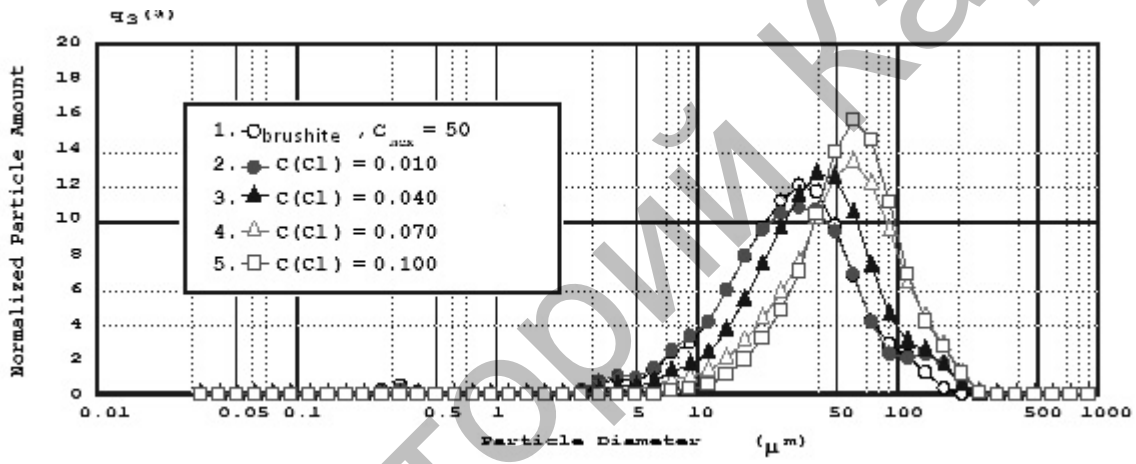
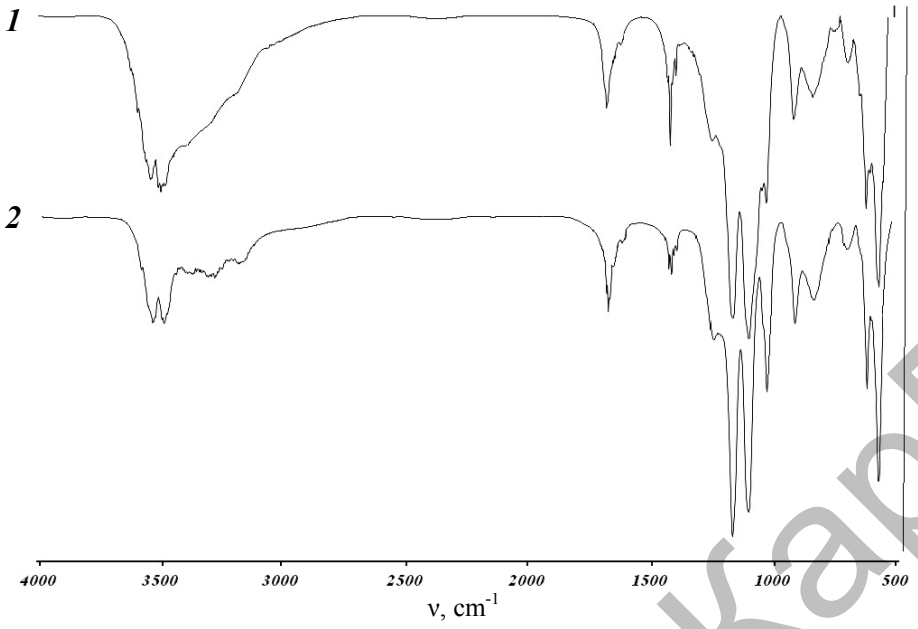


Figure 10. The distribution curve of the particles obtained in the presence of chloride ions (mol/l) in size, μm

The influence of hydrogen carbonate ions on the crystallization ion in the system $Ca(NO_3)_2 – (NH_4)_2HPO_4 – NaHCO_3 – H_2O$. It is known that carbonate ions are a part of the human biological fluid and sometimes may exceed the content of phosphate ions. Therefore, in the following step the influence of hydrocarbonate ions on nature, composition and properties of the precipitated solid phase was studied. The additive concentration ranged from 0.010 to 0.100 mol/l. The investigation by the method of IR-Fourier spectroscopy of the phase composition of the samples obtained from the systems with additives HCO_3^- showed that obtained precipitations are formed with brushite with the admixture of a minor amount of hydroxyapatite, the spectrum is similar (Fig. 9). At this stage of the experimental study it was found that added to the crystallization medium hydrocarbonate ions lead to the precipitation of brushite with the impurity of hydroxyapatite. The increase in the content of the ions of additives in the precipitation is caused by their adsorption on the surface of the solid phase.

The influence of silicate-ions on the crystallization in the system $Ca(NO_3)_2 – (NH_4)_2HPO_4 – Na_2SiO_3 – H_2O$. It is assumed that the bioactivity of the materials is defined by their chemical composition, crystal morphology and properties of surface materials. Therefore, the primary method of managing this property is the chemical modification of calcium orthophosphates. By the example of glass-ceramics produced in the system $CaO–Na_2O–SiO_2–P_2O_5$, it is known that the presence of silicon in the material and at its surface accelerates the union of the implant with the bone. Thus, the use of these materials in medical applications is very promising.

The analysis of the IR-Fourier spectroscopy of the samples with the addition of silicate-ions showed that all precipitations are monophasic and formed by brushite (Fig. 11). There are groups of absorption bands that are characteristic for brushite on the spectra of the obtained samples.



1 — $C(SiO_3^{2-})_{initial}$ = 0.001 M; *2* — $C(SiO_3^{2-})_{initial}$= 0.015 M

Figure 11. IR-spectrum of synthesized phase in the presence of silicate-ions

The study of the influence of organic anions on the properties of synthetic solid phase and characteristics of precipitation process

There are numerous organic components of human biological fluid. It contains simple (albumins, globulins), compound (glycoproteins) proteins, proteins and non-protein nitrogen-containing components — amino acids, urea, et al., as well as carbohydrates and the products of their transformation (pyruvic, citric and acetic acids), vitamins, hormones, lipids, ferment (glycoproteins, mucin, immunoglobulin A, phosphatases, lysozyme, hyaluronidase, ribonuclease and others) [7]. Protein acid-base buffer system plays a role of neutralization, combining the protons of acids with negatively charged groups of aspartate and glutamate: $COO^- + H^+ \leftrightarrow COOH$; the bases are neutralized by a protonated group of radicals of lysine and arginine with the formation of a free amino group and a water molecule: $RN^+H + OH^- \leftrightarrow RNH_2 + H_2O$. The proteins fulfill important functions related to the protection, mineralization processes and participation in digestion. The content of proteins varies within 0.95 — 6.30 g/l according to different authors [6, 7].

The influence of acetate-, citrate- and pyruvate-ions on the crystallization of the solid phase. Three series of syntheses were conducted to study the influence of acetate-, citrate- and pyruvate-ions on the crystallization process of brushite. Organic additives were added into the investigated system $Ca(NO_3)_2$ – $(NH_4)_2HPO_4$ – H_2O in the form of sodium salts of the acids, wherein the additive concentration was varied in the range of 10 to 200 mmol/l.

According to IR-Fourier spectroscopy it was revealed that the precipitation of the basic calcium phosphate — hydroxyapatite occurs in the presence, in the medium of crystallization, of additives along with brushite. The increase in the content of impurity ions does not affect the phase composition of the samples. Thus, when the concentration of the additive changes in the range from 10 to 200 mmol/l, after 2 days of maturation, the solid phase is a mixture of brushite and hydroxyapatite (Fig. 12). It is indicated by the joint presence of the absorption bands that are characteristic for these calcium phosphates on the spectra of the samples.

With IR-Fourier spectroscopy it was revealed that under chosen conditions of the synthesis, the impurity ions introduced in the system cause joint crystallization of two calcium phosphates of different stoichiometry. Adsorptive interaction of the ionized form of the additive with the charged regions of the surface of the solid phase leads to the blocking of the active centers of the growth of brushite crystals and the inability of their advancement, i.e. the change of the composition and a more streamlined structure, resulting in the precipitation of an additional phase of apatite.

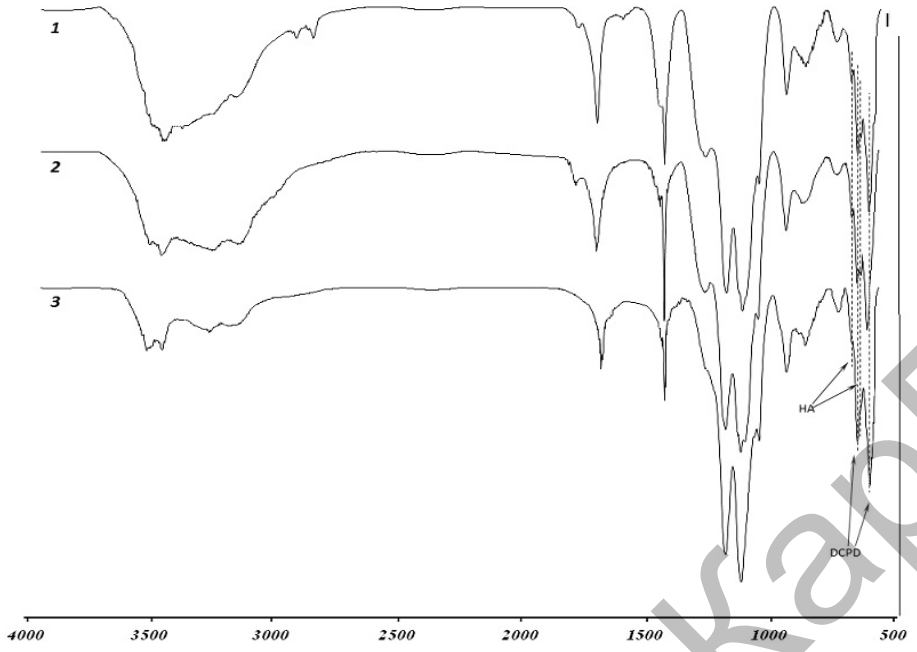


Figure 12. IR-spectra of the synthetic phases obtained in the presence of acetate (1), citrate (2) and pyruvat-ions (3), 200 mkM

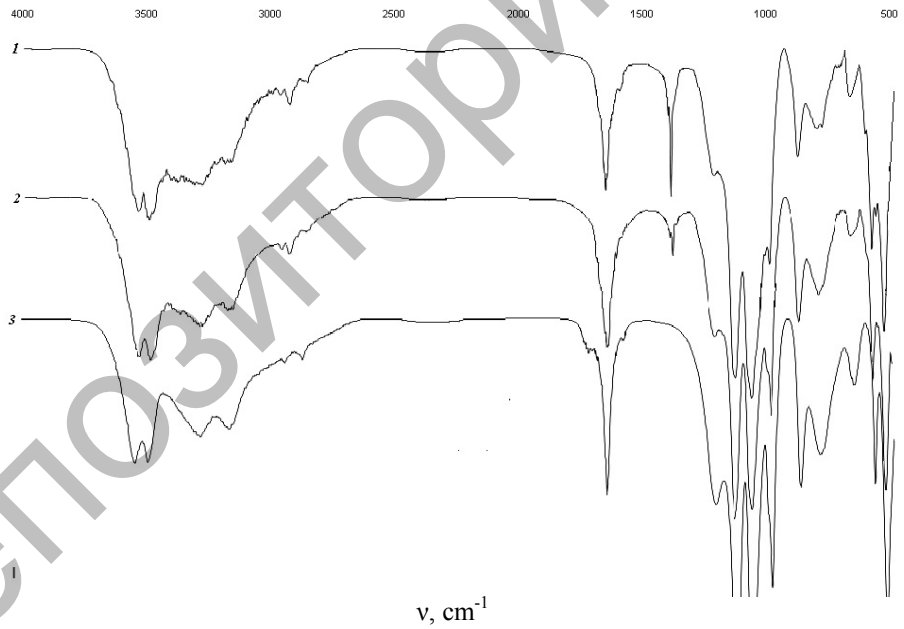


Figure 13. IR-spectra of the synthetic phase obtained in the presence of glucose (1), $C_{initial}$ = 90 mg/l; casein (2), $C_{initial}$ = 1 g/l; gelatin (3), $C_{initial}$ = 2 g/l

The influence of glucose, casein and gelatin on the crystallization of the solid phase. Further we explored the mechanism of the influence of gelatin additives ($C_{initial}$ = 0.5–2.0 g/l), glucose ($C_{initial}$ = 1.8–90 mg/l) and casein ($C_{initial}$ = 0.10–1.00 g/l), the concentration of the latter was chosen based on the data in the composition of human stomatic fluid on the processes of crystallization of the solid phase.

According to the data of IR-spectroscopy, it was established that brushite is present in the composition of precipitations (Fig. 13). Organic component is found in all samples along with the mineral component. On the IR spectra of the samples, the absorption bands of vibrations of bonds of inorganic and organic groups

are found: 1010–1050, 600, 570, 480 cm^{-1} — stretching vibrations and deformation vibrations of the bond O–P–O– PO_4^{3-}ions; 1420–1460 cm^{-1} — CO_3^{2-} and NO_3^- ions; doublet, characteristic for vibrations of the CH bond — in 2980, 2940 cm^{-1}; the absorbance at 640 cm^{-1} — OH. In the near-spectrum region, the intensity is 1650 cm^{-1}, while in the farther there is a broad band of 3150–3400 cm^{-1} corresponding to the vibrations of molecular water.

The conducted studies enabled establishing that the nature of the influence of the organic additives is similar. Organic molecules introduced into the crystallization medium, cause the precipitation of dicalcium phosphate dihydrate with the impurity of apatite phase. Adsorbed on the surface of the solid phase, they inhibit the centers of growth of the germinal crystals of brushite. In addition, there is a possibility for the formation of hydroxyapatite due to the fact that this phase is little resistant under the experimental conditions. As a result, the residual supersaturation of the system is removed by the formation of apatite phase.

Thus, the influence of components of human biological fluids on the possibility and the regularities of the process of precipitation of brushite has been researched. It has been established that the nature of influence of inorganic anions (fluorides, chlorides, hydrocarbonates, silicates) is associated with the change of the phase composition of the crystallizing substance. The influence of organic matter on the process of crystallization is realized by the adsorption mechanism.

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Брушиттің сулы ерітінділерден тұнбаға түсу процесінің мүмкіндігі мен заңдылықтарына бейорганикалық және органикалық қоспалардың әсерін зерттеу

Мақалада термодинамикалық есептеулер және тәжірибелік материал негізінде брушиттің қоспалар қатысында кристалдану ерекшеліктерімен байланысты мәселелер комплексі қарастырылды. Ca^{2+} – HPO_4^{2-} – H_2O – қоспалар жүйесіндегі фазатүзілу заңдылықтары компоненттердің концентрациялары

және pH-тың әр түрлі мәндерінде зерттелді. Кристалданатын фазаның құрамына және тұнбаға түсуіне силикат-, фторид-, хлорид- және гидрокарбонат-иондарының әсері зерттелді. Бастапқы жүйеден брушит және кальцийдің басқа фосфаттарының бірігіп тұнбаға түсетіні көрсетілді. Органикалық қоспалардың әсерін зерттеген кезде олардың брушиттің апатитті фаза қоспаларымен бірге тұнбаға түсетіні анықталды.

О.А.Голованова, М.В.Куимова

Изучение влияния неорганических и органических добавок на возможность и закономерности процесса осаждения брушита из водных растворов

В статье на основе термодинамического расчета и экспериментального материала рассмотрен комплекс проблем, связанных с особенностями кристаллизации брушита в присутствии добавок. Исследованы закономерности фазообразования в системе Ca^{2+} – HPO_4^{2-} – H_2O – добавки в широком интервале варьирования концентраций компонентов и pH. Изучено влияние силикат-, фторид-, хлорид- и гидрокарбонат-ионов на осаждение и состав кристаллизующейся фазы. Получено, что из исходной системы совместно осаждаются брушит и другие фосфаты кальция. При изучении влияния органических добавок установлено, что их присутствие приводит к осаждению брушита с примесью апатитовой фазы.

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