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Synthesis of Pure Hydroxyapatite by Ion Exchange Reaction

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An ion-exchange reaction for the synthesis of hydroxyapatite (HAP) in a constant alkaline medium using preliminary dry homogenization is proposed in this work. Sodium hydrogen phosphate Na_2HPO_4, calcium chloride $CaCl_2$ and calcium hydroxide $Ca(OH)_2$ were chosen as precursors. When Na_2HPO_4 interacts with calcium salts in an alkaline medium, Na^+ ions are replaced by Ca^{2+} ions. The $CaCl_2$ salt was chosen as the source of Ca^{2+} ions, since in this case one of the reaction products is sodium chloride, which is subsequently easily washed out. The required pH of the medium was achieved by adding calcium hydroxide to the starting materials, which was also a source of Ca^{2+} ions. Heating in a water bath provided a constant influx of water molecules, which is necessary for the dissociation of the molecules of the substances involved in the reaction. In dry synthesis, it is rather difficult to obtain stoichiometric HAP due to the uneven distribution of ions in the reacting mixture. The chemical reaction in a humid environment can reduce the influence of this factor. It was assumed that since, in addition to HAP, the reaction products are water-soluble compounds, a slight change in the ratio of the starting components can be used to control the stoichiometry of HAP, as well as the ratio of the final reaction products. Additional products formed during the reaction were removed by washing the resulting powder with distilled water. The washed and dried HAP powder was annealed in an oven at $T = 700$ °C. Studies carried out by methods of X-ray phase analysis, scanning electron and transmission microscopy showed that the material obtained is a single-phase hydroxyapatite powder with a Ca/P ratio close to 1.67. It was found that the particles of HAP powder obtained as a result of synthesis with subsequent washing have the shape of needles with a thickness of 10 to 40 nm and a length of 30 to 200 nm. Annealing of the powder at a temperature of 700 °C leads to agglomeration of particles, as well as to rounding of their shape.

Keywords: Nanocrystalline hydroxyapatite, Phase and elemental composition, X-ray phase analysis.

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1. INTRODUCTION

Currently, one of the priority areas of modern materials science is the creation of high-quality biocompatible materials for their further use in medicine. Hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ (HAP) is one of such materials. HAP is widely used in modern dentistry, traumatology and orthopedics, displacing metals and other materials traditionally used here due to its elemental composition, close to the composition of the bone tissue of a living organism, and high biological compatibility. HAP can be obtained by various methods [1], among which there are methods of "wet" chemistry carried out by precipitation of HAP from solutions or suspensions containing HAP-forming ions at $pH > 7$. These methods include sol-gel method [2-5], as well as the method of hydro- (solvo-) thermal synthesis [6-8]. There are also solid-phase synthesis methods in which reactions occur between dry precursors converted to HAP as a result of high-temperature annealing (1050-1250 °C) [9, 10] or mechanochemical method [11-12], which consists of prolonged mixing and grinding of components, containing the necessary ions, in ball mills. Most of these methods are energy-consuming, or they use components that are harmful to humans. Our task was to carry out the synthesis of HAP using a non-expensive method and non-toxic precursors.

2. EXPERIMENTAL TECHNIQUE

We used a combined method in which the starting components were initially mixed in dry to obtain HAP. Then, distilled water was added to the resulting mixture of dry precursors in the amount of 50 wt. % of dry components. The result was a moist, porridge-like mass. The resulting mixture was heated in a water bath for 2 hours stirring occasionally. The water tank was covered with a flask-cap (Fig. 1). The following substances were selected as precursors: sodium hydrogen phosphate ($Na_2HPO_4 \cdot 12H_2O$), calcium chloride ($CaCl_2$) and calcium hydroxide ($Ca(OH)_2$).

Na^+ ions are replaced by Ca^{2+} ions during the interaction of $Na_2HPO_4 \cdot 12H_2O$ with calcium salts in an alkaline medium. The $CaCl_2$ salt was chosen as the source of Ca^{2+} ions, since in this case one of the reaction products is sodium chloride, which is subsequently easily washed out. The required pH of the medium was achieved by adding calcium hydroxide to the starting materials, which was also a source of Ca^{2+} ions. Heating in a water bath in a closed container provided a constant additional influx of water molecules, which is necessary for the dissociation of the molecules of substances involved in the reaction. In dry synthesis, it is rather difficult to obtain stoichiometric HAP due to the uneven distribution of ions in the reacting mixture. The chemical reaction in a humid environment can reduce the influence of this factor.

The ratio of precursors was selected from the calculation of the stoichiometry of the reaction. The synthesis was carried out according to the scheme:

$$6Na_2HPO_4 \cdot 12H_2O + 6CaCl_2 + 4Ca(OH)_2 \rightarrow Ca_{10}(PO_4)_6(OH)_2 + 12NaCl + 18H_2O.$$

The resulting reaction product was thoroughly washed with distilled water at room temperature. Washing was repeated many times. This is necessary to remove sodium chloride from the resulting product, which is formed during the synthesis. The washed product was dried in air at $T = 150$ °C for 3 hours. After drying, the resulting powder was ground and annealed in ceramic dishes in a muffle furnace according to the scheme: *heating* – 4 hours to a temperature of 700 °C; *isothermal exposure* – 1 hour; *cooling* – to room temperature (during 6-7 hours).

The elemental and phase composition was monitored at each stage of the technological process to understand the process of the reaction, as well as to control the composition and purity of the products obtained. Samples were taken: immediately after synthesis; after washing and drying; after annealing in a muffle furnace.

At the second and third stages, the structure of the obtained powders was studied.

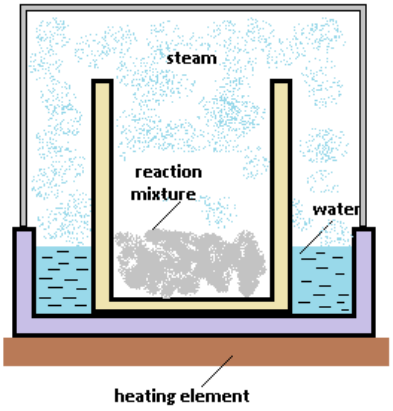

Fig. 1 – Scheme for the synthesis of HAP in a water bath

3. RESEARCH METHODS

The phase-structural analysis was carried out by Cu-K X-ray diffractometry using a RIGAKU ULTIMA-IV X-ray diffractometer. The survey was performed using Bragg-Brentano focusing in the range of angles 2θ from 20 to 80°. The separation of profiles into components was carried out using a software package for quantitative image analysis.

The elemental composition of the powders was determined by analyzing the characteristic X-ray spectra using a spectrometer built into a scanning electron microscope. Quantitative and qualitative elemental analysis was performed using the GENESIS software company EDX, provided together with an X-ray spectrometer. This method allows a qualitative and quantitative analysis of the elemental composition of materials for elements heavier than boron.

The structure and particle size of the obtained powders were investigated using a JEOL JEM 2100 transmission electron microscope. For this, an emulsion in isopropyl alcohol was prepared from the obtained powder. A drop of a suspension of powder in alcohol was dripped onto a thin carbon film, which was placed on a standard copper mesh used in transmission electron microscopy to study non-self-sustaining samples. Electron diffraction images were obtained from the powders under study to analyze their crystallinity also.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 2 shows the diffraction patterns of the obtained powders immediately after synthesis (1), after washing (2), and also after calcination in an oven (3).

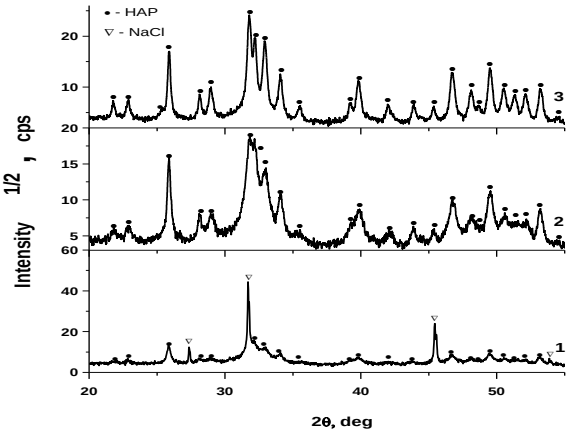

Fig. 2 – X-ray diffraction patterns of the reaction products immediately after synthesis (1), after washing (2) and after calcination (3)

It was found that the result of synthesis from precursors according to the proposed scheme is in accordance with our assumptions. Sodium chloride and hydroxyapatite are in the following ratio: NaCl – 47 %, HAP – 53 % (Fig. 2). The ratio of NaCl to HAP phases was calculated by the Rietveld method.

The results of X-ray studies indicate that both materials obtained i.e. after washing and after calcination are pure (from the point of view of XRD) HAP. A decrease in the width of the peaks of the annealed powder compared with the other two indicates a recrystallization process that occurs during the annealing.

The elemental composition of the obtained powders was controlled using the method of energy dispersive X-ray spectroscopy. This was done in order to verify the absence of chlorine ions in the washed and annealed powders. The presence of a small amount of chlorine ions is not detected by X-ray phase methods, but it is noticeable in the spectrum of characteristic X-ray radiation.

Fig. 3 shows the characteristic X-ray spectra obtained from samples after synthesis, after washing, and after calcination, respectively.

The research results confirm that the synthesis process is carried out according to the proposed scheme. In the washed and annealed powders, the presence of chlorine ions is not observed.

The microstructure of the powders was studied using transmission electron microscopy.

It was found that the particles of the powder obtained as a result of synthesis with subsequent washing have

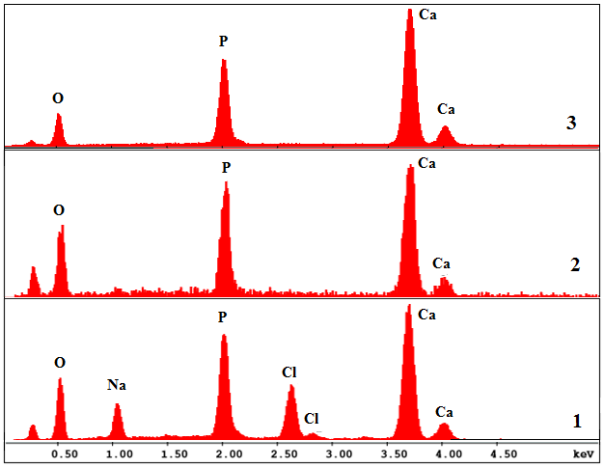

Fig. 3 – Spectra of characteristic X-ray radiation of HAP powders: after synthesis (1), after washing (2), after calcination (3)

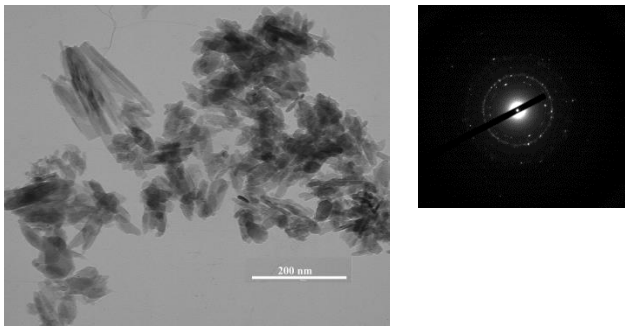

Fig. 4 – Images of the microstructure (left) and electron diffraction (right) of the HAP powder after washing obtained by transmission electron microscopy

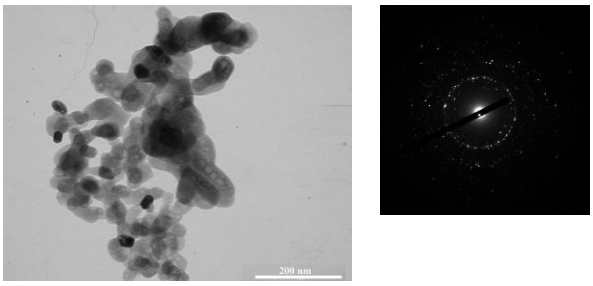

Fig. 5 – Images of the microstructure (left) and electron diffraction (right) of the HAP powder after annealing obtained by transmission electron microscopy

the shape of needles with a thickness of 10 to 40 nm and a length of 30 to 200 nm. This shape is characteristic of particles for HAP.

Annealing of the powder at a temperature of 700 °C leads to agglomeration of particles, as well as to rounding of their shape. The particle size of the HAP powder after annealing varies from 35 to 150 nm.

5. CONCLUSIONS

The possibility of HAP obtaining according to the scheme: $6Na_2HPO_4{\cdot}12H_2O + 6CaCl_2 + 4Ca(OH)_2 \rightarrow Ca_{10}(PO_4)_6(OH)_2 + 12NaCl + 18H_2O$ was confirmed as a result of the studies.

It was found that it is possible to obtain a single-phase HAP with a Ca/P ratio close to stoichiometric after washing the reaction products from soluble impurities. The high purity of the resulting product, as well as the simplicity and low cost of the proposed method, allows it to be used to create commercial technology for the production of HAP.

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Отримання чистого гідроксиапатиту методом іонно-обмінної реакції

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У роботі запропонована іонно-обмінна реакція синтезу гідроксиапатита (ГАП) у постійному лужному середовищі з використанням попередньої сухої гомогенізації прекурсорів. Як прекурсори були обрані гідрофосфат натрію Na_2HPO_4, хлорид кальцію $CaCl_2$ і гідроксид кальцію $Ca(OH)_2$. При взаємодії Na_2HPO_4 з солями кальцію в лужному середовищі відбувається заміщення іонів Na^+ на іони Ca^{2+}. Як джерело іонів Ca^{2+} була використана сіль $CaCl_2$, оскільки в цьому випадку одним з продуктів реакції є хлорид натрію, який згодом легко вимивається. Необхідний pH середовища досягався додаванням у вихідні речовини гідроксиду кальцію, який одночасно був і джерелом іонів Ca^{2+}. Нагрівання на водяній бані забезпечувало постійний приплив молекул води, яка необхідна для дисоціації молекул речовин, що беруть участь в реакції. При сухому синтезі досить складно отримати стехіометричний ГАП через нерівномірність розподілу іонів у реакційній суміші. Перебіг хімічної реакції у вологому середовищі дозволяє зменшити вплив цього фактору. Було зроблено припущення, що оскільки крім ГАП продуктами реакції є розчинні у воді сполуки, то незначною зміною співвідношення вихідних компонентів можна регулювати стехіометрію ГАП, а також співвідношення кінцевих продуктів реакції. Додаткові продукти, що утворюються в ході реакції, видалялися промиванням отриманого порошку дистильованою водою. Відмитий і висушений порошок ГАП відпалювався у печі при $T = 700$ °C. Дослідження, проведені методами рентгенофазового аналізу, растрової електронної та просвічуючої мікроскопії показали, що отриманий матеріал є однофазним порошком ГАП зі співвідношенням Ca/P, близьким до 1,67. Було виявлено, що частинки порошку ГАП, отриманого в результаті синтезу з наступним промиванням, мали форму голок товщиною 10-40 нм і довжиною від 30 до 200 нм. Відпал порошку при температурі 700 °C приводив до агломерації частинок, а також до округлення їх форми.

Ключові слова: Нанокристалічний гідроксиапатит, Фазовий і елементний склад, Рентгенофазовий аналіз.