Calcium acetylacetonate – a novel calcium precursor for sol-gel preparation of $Ca_{10}(PO_4)_6(OH)_2$

Aldona Beganskienė*,

Irma Bogdanovičienė and

Aivaras Kareiva

Faculty of Chemistry,
Vilnius University,
Naugarduko 24, LT-03225 Vilnius,
Lithuania

Calcium hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$, HA) has been synthesized by a new non-aqueous sol-gel process based on calcium acetylacetonate and different phosphorus compounds as starting materials. The samples of $Ca_{10}(PO_4)_6(OH)_2$ were obtained by calcination of the precursor gels for 15 h at 1000 °C. The phase transformations, composition and micro-structural features of the polycrystalline samples were studied by infrared (IR) spectroscopy and X-ray powder diffraction (XRD) analysis. The influence of the nature of phosphorus precursor on the formation of HA at 1000 °C is also discussed.

Key words: biomaterials, hydroxyapatite, sol-gel process, calcium acetylacetonate

INTRODUCTION

Calcium hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, commonly referred to as HA, is one of calcium phosphate based bioceramic materials that makes up the majority of the inorganic components of human bones and teeth. Synthetic HA is known to be one of the most important implantable materials due to its biocompatibility, bioactivity and osteoconductivity coming from the analogy to the mineral components of natural bones, and is used as a substitute material for human hard tissues [1, 2]. For the use in medical practice, the HA ceramics have been conventionally strengthened and toughened in the form of granules and dense or porous ceramics composites, coatings, whiskers and nanorods [3–6].

One of the most important requirement for a material designed for bone substitution and/or repair is the ability to create a bond with the host living bone. Moreover, such bioactive materials should spontaneously bond to and integrate with the bone in the living body [7]. Thus, an improvement of the bone-repairing materials is still required. However specific chemical, structural and morphological properties of HA bioceramics are highly sensitive to the changes in chemical composition and processing conditions [8–10]. During the last decade, a number of papers have been published on different methodologies of the preparation and processing of HA bioceramics. The solid-state synthesis of HA from oxide or inorganic salt powders usually requires extensive mechanical mixing and lengthy heat treatments at high temperatures [11, 12]. These processing conditions, however, do not allow a facile control over micro-structure, grain size and grain size distribution in the resulting powders or shapes. Several wet-

chemical and/or soft chemistry techniques, such as polymerized complex route [13], hydrothermal synthesis [14], precipitation method [15] or spray-, gel-pyrolysis methods [16, 17] have been used to produce HA phases. Most of these methods suffer from the complex and time-consuming procedures and/or mismatch in the solution behaviour of the constituents.

It has been well demonstrated that the sol-gel process offers considerable advantages of good mixing of the starting materials and excellent chemical homogeneity of the product [18]. Several sol-gel approaches starting from non-aqueous solutions of different precursors of calcium and phosphorus have been used for the preparation of HA powders [19–24]. In these synthetic routes, for instance calcium nitrate or different calcium alkoxides were used as calcium precursors. The major limitation for its applications was found to be the very low solubility of the calcium alkoxides in the organic solvents and its low reactivity which caused deviations from the stoichiometry of the final materials. Thus, the objectives of this study were to develop a reliable process for the synthesis of calcium hydroxyapatite using the non-aqueous sol-gel technique, to optimize the synthesis conditions using a new calcium precursor and to investigate the influence of the nature of phosphorus precursor on the formation of the end product.

EXPERIMENTAL

In the sol-gel processing of hydroxyapatite, calcium acetylacetonate dihydrate ($Ca(C_5H_7O_2)_2 \cdot 2H_2O$) and different alkyl phosphates or phosphites have been chosen as Ca and P precursors, respectively. The phosphorus precursors and solvents are listed in Table. Calcium acetylacetonate was prepared according to the previously published procedure [25]. The mixture of calcium

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* Corresponding author. E-mail: aldona.beganskiene@chf.vu.lt

Table. **Phosphorus precursors used in the sol-gel processing**

No.	Phosphorus compunds		Solvent
	Name	Formula	
1.	Trimethyl phosphate	$(CH_3O)_3PO$	$EtOH/H_2O$ (4:1)
2.	Tributyl phosphate	$(C_4H_9O)_3PO$	$EtOH/H_2O$ (4:1)
3.	Triethyl phosphite	$(C_2H_5O)_3P$	EtOH
4.	Diethyl phosphite	$(C_2H_5O)_2POH$	EtOH
5.	Diisopropyl phosphite	$(C_3H_7O)_2POH$	EtOH
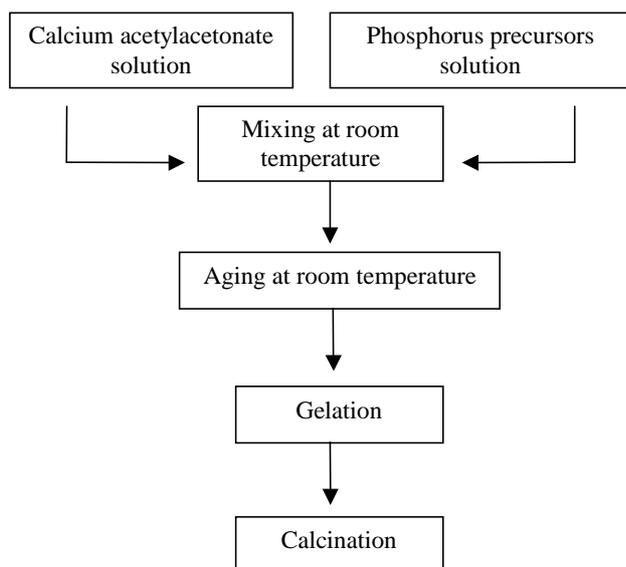
Fig. 1. Flow chart of the preparation of calcium hydroxyapatite by the sol-gel route

Fig 2. The IR spectra of the Ca–P–O gels obtained from (*a*) trimethyl phosphate, (*b*) tributyl phosphate, (*c*) triethyl phosphite precursors and calcined at different temperatures

nitrate tetrahydrate (5 g; 0.02 mol) and 2,4-pentadione (7 g; 0,07 mol) was dissolved in 25 ml of distilled water. Simultaneously, ammonium hydroxide was added drop–wise into the reaction solution until the value of pH reached 9. The precipitates were collected and washed three times with distilled water. The obtained calcium acetylacetonate dihydrate was mixed with P precursor for the synthesis of hydroxyapatite. The molar ratio of Ca/P was 1.67. The solution of phosphorus precursor (0.03 mol in 15 ml of alcohol or mixture of alcohol-water) was added dropwise to the stirred calcium acetylacetonate solution (0.05 mol in 25 ml of alcohol). The sols were mixed and aged for 2 h at room temperature. Then the solutions were concentrated by slow evaporation at 65 °C. The dried gels were ground in an agate mortar and calcined at 250 °C for 6 h in the air. The dried gels were annealed at different temperatures (400, 600, 750 and 1000 °C) for 3 h. The schematic flow chart of the synthesis is presented in Fig. 1.

The infrared spectra (IR) were recorded in KBr powders using a Perkin–Elmer Spectrum BX FT-IR spectrometer. The samples were characterized by powder X-ray diffraction analysis (XRD) performed with a D8 Bruker AXS powder diffractometer using CuKα_1 radiation obtained with a multilayer Ni/C monochromator.

Fig. 3. The IR spectra of the Ca-P-O gels obtained from (*a*) diethyl phosphite, (*b*) diisopropyl phosphite and calcined at different temperatures
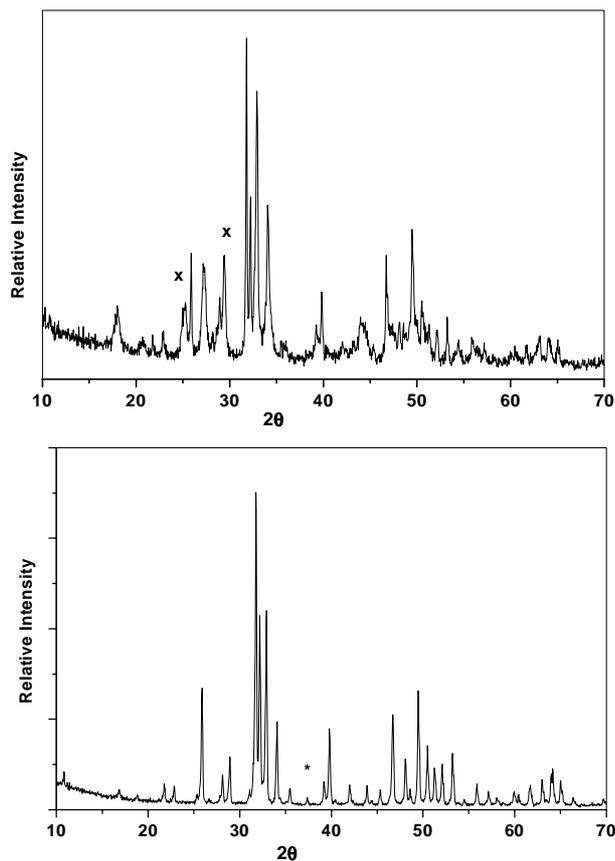
Fig. 4. X-ray diffraction patterns of HA ceramic samples derived from tributyl phosphate (*top*) and diisopropyl phosphite (*bottom*). Impurity phases are marked: (x) $CaCO_3$ and (*) CaO

RESULTS AND DISCUSSION

It is well known that IR analysis of synthesized samples is important both for control of the reaction process and properties of the materials obtained [26]. In the sol-gel process the calcium and phosphorus compounds used as starting materials are converted through the hydrolysis and condensation reactions to amorphous gels which are further transformed to ceramics when heated at relatively low temperatures. As already mentioned, the formation of calcium hydroxyapatite ceramics was also investigated depending on the nature of the source of phosphorus. The IR spectra of the Ca–P–O gel samples obtained from trialkyl and dialkyl phosphorus precursors and calcined at different temperatures (400, 600, 750 and 1000 °C) are shown in Figs. 2 and 3, respectively. As one can see, all IR spectra contain a broad band at ~3570–3450 cm^{-1}, which can be assigned to the adsorbed water. In some spectra, the peaks at ca. 2350 cm^{-1} are well pronounced, arising from carbon dioxide from the atmosphere. The IR spectra of the samples heated at 400 °C exhibited featureless bands, which indicated a disordered environment. However, all IR spectra contain the bands centred at about 1000–1105 cm^{-1}, assignable to the initial formation of hydroxyapatite. The intensity of these bands slightly increases in the IR spectra of the samples obtained at 600 °C. The bands
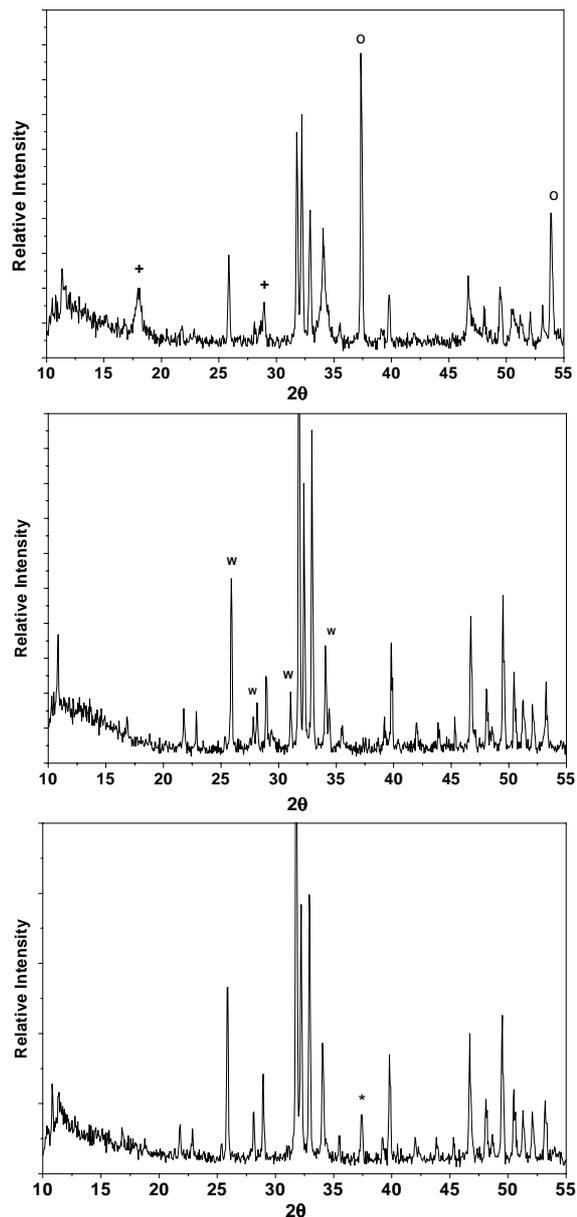
Fig. 5. X-ray diffraction patterns of HA ceramic samples derived from trimethyl phosphate (*at top*), triethyl phosphite (*centre*) and diethyl phosphite (*bottom*). Impurity phases are mark-ed: (+) $Ca(OH)_2$; (o) CaO (w) $Ca_3(PO_4)_2$ and (*) unidentified

at 1590, 1420, and 870 cm^{-1} correspond to the vibration in the carbonate ion. The carbonate peaks in the IR spectra of the Ca–P–O samples persist to 750 °C, but with a lower intensity than before. How-ever, in the case of tributyl phosphate used as a starting material, the bands attributable to CO_3^{2-} remain very intensive (see Fig. 2b). The IR spectra of HA samples from trimethyl phosphate (Fig. 2a), triethyl phosphite (Fig. 2c) and diethyl phosphite (Fig. 3a) calcined at 1000 °C do not show any bands attributable to carbonates. However, in the case of diisopropyl phosphate (Fig. 3b), very weak carbonate vibrations could still be detected. Moreover, the IR spectrum of the sample obtained from tributyl phosphate at 1000 °C is

almost identical to the previous one for the sample synthesized at a lower temperature, showing rather intensive bands attributable to the ionic carbonate vibrations.

In summary, the IR spectra of the HA samples obtained at 1000 ℃ using calcium acetylacetonate and different phosphorus compounds as starting materials indicate the formation of a typical HA structure containing sharp O–H and P–O bands [27]. The spectra of all ceramic samples obtained at 1000 ℃ clearly show the bands of a significant intensity at 1048 cm^{-1} and 1092 cm^{-1}. These bands arise due to the factor group splitting of the n_3 fundamental vibrational mode of the PO_4^{3-} tetrahedral [28]. The bands at ~956–960 cm^{-1} and at ~565–600 cm^{-1} correspond to n_1 and n_4 symmetric P–O stretching vibration of the PO_4^{3-} ion, respectively [15, 17, 28]. Moreover, the bands assigned to the stretching modes of hydroxyl groups (OH) in hydroxyapatite (3570 cm^{-1} (strong), 630 cm^{-1} (weak)) [15, 17, 29, 30] are clearly observed in the spectra. Thus, according to the stretching frequencies observed and the similarity of the IR spectra of the investigated samples, a possible formation of crystalline HA by all synthesis routes could be suggested.

The sintering of the Ca–P–O precursor gels using different starting materials of phosphorus at 1000 ℃ produced fully crystallized $Ca_{10}(PO_4)_6(OH)_2$ ceramics. However, some of the decomposition products or impurity phases were detected in all HA powders. The XRD patterns of calcium hydroxyapatite powders obtained by calcinating and sintering at 1000 ℃ of Ca-P-O gels derived from the tributyl phosphate and diisopropyl phosphite precursors were recorded in the region of $2\theta \approx 10$–70 degrees (Fig. 4). The three most intensive lines ((211), (300), and (112)) are located between $2\theta \approx 31$–33 degrees, as noted in the previous reports [27–30]. These results are also in good agreement with the reference data for $Ca_{10}(PO_4)_6(OH)_2$ (PDF [74–566]). However, some unindexed lines could also be observed. The HA sample obtained from tributyl phosphate contains a large amount of $CaCO_3$. This is not surprising because, as mentioned previously, the IR spectrum of this sample contains very intensive vibrations attributable to carbonate. Weak absorbance due to carbonate has also been noted in the IR spectrum of the HA sample synthesized using diisopropyl phosphite as a P source. How-ever, the reflections from $CaCO_3$ in the XRD pattern of this specimen due to small concentration are not detectable. Only a minor amount of CaO as impurity phase could be determined. Thus, the obtained IR results are completely consistent with the crystallization process observed by XRD measurements.

The XRD patterns of HA synthesized using trimethyl phosphate, triethyl phosphite and diethyl phosphite as P precursors in the sol-gel process were recorded in the region of $2\theta \approx 10$–55 degrees and are shown in Fig. 5. Again, $Ca_{10}(PO_4)_6(OH)_2$ was found to be the main crystalline phase in all synthesis products. It is interesting to note that the side phases such as $Ca(OH)_2$,

CaO or $Ca_3(PO_4)_2$ are detected in all XRD patterns. As seen from the XRD patterns, the smallest amount of secondary phases contain HA samples obtained by the calcination of gels derived from calcium acetylacetonate and dialkyl phosphates. So, the obtained results allow us to conclude that the reason for the presence of impurity phases in HA is a lack of stoichiometry within the starting precursor gels due to the low hydrolysis rate of trialkyl phosphates or phosphite. The higher hydrolysis rate of the diethyl and diisopropyl phosphites allows to reduce the initial time for the complexation of calcium acetylacetonate with phosphorus compounds.

CONCLUSIONS

The present study shows, for the first time to the best of our knowledge, that calcium acetylacetonate could be successfully used as a calcium source for the sol-gel preparation of calcium hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$, HA) ceramics. HA samples were synthesized at 1000 ℃ by using in the sol-gel processes the mixtures of calcium acetylacetonate and different phosphorus precursors (trimethyl and tributyl phosphates, and triethyl, di-ethyl and diisopropyl phosphites). It was also clearly demonstrated that the phase purity of the synthesized products could be controlled by changing the nature of phosphorus precursors. Almost monophasic $Ca_{10}(PO_4)_6(OH)_2$ samples were obtained during of the calcination the gels derived from the mixtures of calcium acetylacetonate and dialkyl phosphates. The use of trialkyl phosphates as the starting materials, how-ever, resulted in the formation of a higher amount of side phases in the end products. It was concluded that the reason for the presence of impurity phases in HA is a lack of stoichiometry within the starting precursor gels due to the low hydrolysis rate of trialkyl phosphorus salts.

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**Aldona Beganskienė, Irma Bogdanovičienė,
Aivaras Kareiva**

KALCIO ACETILACETONATAS – NAUJA PRADINĖ MEDŽIAGA ZOLIŲ-GELIŲ METODU SINTETINANT $Ca_{10}(PO_4)_6(OH)_2$

S a n t r a u k a

Šiame darbe pasiūlytas naujas kalcio hidroksiapatito ($Ca_{10}(PO_4)_6(OH)_2$) zolių-gelių sintezės nevandenėje terpėje metodas, kalcio šaltiniu naudojant kalcio acetilacetonatą. Fosoforo pradinėmis medžiagomis buvo naudojamos įvairios dialkil- arba trialkil druskos (trimetil- ir tributilfosfatai bei trietil-, dietil- ir diizopropilfosfitai). Kalcio hidroksiapatito pavyzdžiai buvo susintetinti kaitinant pradinius gelius 15 val. 1000°C temperatūroje. Susintetintiems pavyzdžiams apibūdinti taikyti infraraudonosios spektroskopijos ir rentgeno spindulių difrakcinės analizės metodai. Parodyta, kad kalcio hidroksiapatito fazinis grynumas labai priklauso nuo zolių-gelių procese naudojamo alkilfosfato prigimties. Dialkilfosfatų atveju pavyko susintetinti beveik vienfazį $Ca_{10}(PO_4)_6(OH)_2$.