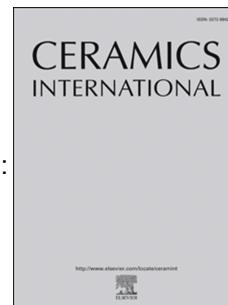


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Effect of washing procedure

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**Controllable synthesis of tricalcium phosphate (TCP) polymorphs by  
wet precipitation: effect of washing procedure**

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**Abstract**

In the present work effect of processing conditions on the synthesis of tricalcium phosphate (TCP) polymorphs was investigated. Pure  $\alpha$ - and  $\beta$ -TCP polymorphs were prepared by wet precipitation method at almost identical thermal conditions. It was shown that formation of the compound with desired crystalline structure can be achieved by applying a washing procedure with a certain solvent to as-prepared calcium phosphate precipitates. Effect of water, acetone, acetonitrile, ethanol and isopropanol on the crystallinity and crystal structure of the as-prepared and annealed powders was studied. It was demonstrated that type of the washing liquid strongly affects crystalline or amorphous nature of the as-prepared precipitates and formation of different TCP polymorphs after thermal treatment. Washing of the as-prepared precipitates with water and acetone leads to the formation of  $\beta$ -TCP, while washing with acetonitrile and alcohols leads to the crystallization of  $\alpha$ -TCP. The thermal behavior of dried precipitates was investigated by thermogravimetric analysis (TGA). The crystallinity, crystal structure and structural changes were evaluated by X-ray powder diffraction (XRD), Fourier-transform infrared (FTIR) and Raman spectroscopy. Scanning electron microscopy (SEM) was used for the characterization of morphological features of the synthesized products.

*Keywords:* Tricalcium phosphate, TCP, processing conditions, polymorphs, washing procedure.

## 1. Introduction

Nowadays calcium phosphate (CP) biomaterials attract huge attention in the field of regenerative medicine. Due to the compositional similarity to the mineral phase of bones and excellent biocompatibility, different synthetic CPs have been widely used as biomaterials for bone repair [1]. Moreover, CPs have attracted significant interest in simultaneous use as bone substitute and drug delivery vehicle, adding a new dimension to their applications [2, 3]. Among synthetic CPs currently used as biomaterials, the most popular are calcium hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ , HA), calcium-deficient HA ( $\text{Ca}_{10-x}(\text{PO}_4)_{6-x}(\text{HPO}_4)_x(\text{OH})_{2-x}$ , CDHA) and tricalcium phosphate ( $\text{Ca}_3(\text{PO}_4)_2$ , TCP) [4-6]. Some of these materials under certain conditions are able to transform from one to another [7-10].

TCP has 3 polymorphs, however only 2 of them can be stabilized at room temperature –  $\alpha$ - and  $\beta$ -TCP.  $\alpha$ -TCP crystallizes in the monoclinic crystal system with the space group  $P2_1/a$ , while  $\beta$ -TCP crystallizes in the rhombohedral crystal system with the space group  $R3c$  [11].  $\beta$ -TCP has denser structure and its theoretical density is  $3.066 \text{ g/cm}^{-3}$  against  $2.866 \text{ g/cm}^{-3}$  of  $\alpha$ -TCP. Both TCP polymorphs are used for medical purposes, however, due to the different physicochemical properties these materials are used for different applications. In aqueous media  $\alpha$ -TCP hydrolyzes with transformation to CDHA and due to this high reactivity it is often used in bone cements as a major powder component [12, 13].  $\beta$ -TCP in its turn is widely used for the fabrication of mono- or biphasic (as a rule comprise  $\beta$ -TCP and HA mixture) bioceramics [14, 15].

Most frequently  $\beta$ -TCP is synthesized by solid state reaction or wet precipitation methods at temperatures about  $800 \text{ }^\circ\text{C}$  and higher [16, 17].  $\alpha$ -TCP in its turn is usually prepared by annealing Ca and P precursor mixture at temperatures above  $1125 \text{ }^\circ\text{C}$ ,

which is the temperature of the phase transition from  $\beta$ -TCP to  $\alpha$ -TCP [18, 19]. Additional difficulties to high-temperature treatment disadvantages causes the nature of this phase transition, which is reversible and very sensitive to impurities and processing conditions [9, 10, 20]. Thermal quenching is commonly used in order to stabilize metastable  $\alpha$ -TCP polymorph [21, 22]. However, it was shown that  $\alpha$ -TCP can be also obtained at such low temperatures as 600–700 °C with further transformation to  $\beta$ -TCP at around 800 °C [23]. Thereby  $\alpha$ -TCP can be synthesized at both high and low temperatures having  $\beta$ -TCP polymorph at intermediate temperatures.

It is well known that processing conditions can drastically affect structure, morphology and physicochemical properties of materials [24-29]. Previously, investigation of the formation of various CPs from calcium propionate and triethyl phosphate was reported by Kjellin *et al.* [30]. It was shown that different materials such as  $\beta$ -TCP, CDHA, monetite or amorphous calcium phosphate (ACP) can be obtained depending on water content in a reaction mixture. Duncan *et al.* investigated the role of the chemical composition of monetite on the synthesis and properties of  $\alpha$ -TCP [31]. It was concluded that the ratio of  $\alpha$ - and  $\beta$ -TCP polymorphs prepared by solid state reaction synthesis method depends on purity of starting materials, and properties of phase pure  $\alpha$ -TCP may be indirectly affected by purity of the chemicals. Lau *et al.* proposed a phase-tunable synthesis of CPs by hydrothermal/solvothermal method [32]. Utilization of water, methanol and ethanol as reaction solvent resulted in a formation of HA,  $\beta$ -TCP or anhydrous dicalcium phosphate, respectively. Recently, effect of reaction solvents such as distilled water, tetrahydrofuran and N,N-dimethylformamide on sol-gel derived HA powders was studied [33]. Chemical structure and morphology of the obtained products were found to be strongly dependent on the dielectric constant and polarity of

the solvent. Li *et al.* studied the influence of polyethylene glycol addition to the reaction mixture on the synthesis of  $\beta$ -TCP [34]. The results showed that the polyethylene glycol played an important role in improving the purity and dispersity of  $\beta$ -TCP powders.

In the present work we report on the effect of washing procedure of the as-prepared CP precipitates on the synthesis of TCP polymorphs. While majority of studies are focused on the effect of different solvents during chemical reaction, we present the influence of different solvents already after precipitation reaction. Water, acetone, acetonitrile, ethanol and isopropanol were chosen to investigate the influence of the washing liquids on the thermal behavior, structure, composition and morphology of initial precipitates and final materials. It was shown that synthesis of desired pure TCP polymorph can be easily controlled by washing of the as-precipitated species with particular solvent.

## 2. Materials and methods

### 2.1. Synthesis

All compounds were synthesized by wet precipitation method using calcium nitrate tetrahydrate ( $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ,  $\geq 99\%$ , Roth) and diammonium hydrogen phosphate ( $(\text{NH}_4)_2\text{HPO}_4$ ,  $\geq 98\%$ , Roth) as starting materials. For all experiments Ca to P ratio was kept 1.50 and amount of taken precursors was calculated for preparation of 1.5 g of final TCP product. For the synthesis an appropriate amount of  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  was dissolved in deionized water resulting in 0.75 M solution. Next, concentrated ammonia solution ( $\text{NH}_4\text{OH}$ , 25%) was added to the above solution in order to adjust pH to 10. In parallel 0.5 M  $(\text{NH}_4)_2\text{HPO}_4$  solution in deionized water was prepared. Next, under constant stirring on magnetic stirrer, the prepared solutions were mixed together resulting in the instant formation of white precipitates. The obtained precipitates were

stirred in the reaction mixture for 10 minutes, afterwards vacuum filtered and washed with a certain solvent. First, all precipitated species were always washed with 100 mL of deionized water following by washing with different volumes (20, 40, 60, 80 and 100 mL) of deionized water, acetone (AC,  $\geq 99.8\%$ , Roth), acetonitrile (ACN,  $\geq 99.5\%$ , Roth), ethanol (EtOH, 96%, Roth) or isopropanol (i-PrOH,  $\geq 99.5\%$ , Roth). Additional washing with deionized water was performed in order to ensure the same sum volume and washing time for all solvents. All synthesis and washing procedures were performed under identical conditions using the same Buchner funnel and cellulose filters (55 mm in diameter, retention range – 5–13  $\mu\text{m}$ ). After washing the precipitates were dried at 50 °C overnight in the oven. Finally, dry powders were ground in agate mortar and annealed in the furnace for 5 h in air.

## 2.2. Characterization

Powder X-ray diffraction data were collected using Ni-filtered Cu  $K\alpha$  radiation on Rigaku MiniFlex II diffractometer working in Bragg-Brentano ( $\theta/2\theta$ ) geometry. The data were collected within  $2\theta$  angle range from 10 to 60° at a step width of 0.01° and speed of 2°/min. Lattice parameters were refined by the Rietveld method using the FullProf suite in the profile matching mode. The average crystallite size ( $\tau$ ) was calculated by Scherrer equation:

$$\tau = \frac{0.9\lambda}{B\cos\theta} \quad (1)$$

where  $\lambda$  is the X-ray wavelength, B is the full width at half maximum (FWHM) of a diffraction peak and  $\theta$  is the Bragg angle. The thermal decomposition of the as-prepared precipitates was analyzed through thermogravimetric (TG) analysis using Perkin Elmer STA 6000 Simultaneous Thermal Analyzer. Samples of about 5–10 mg were heated from 25 to 900 °C at a heating rate of 10 °C/min in a dry flowing air (20 mL/min).

Infrared (FTIR) spectra were recorded in the range of 3000–400  $\text{cm}^{-1}$  employing Bruker ALPHA ATR spectrometer. Raman spectroscopy measurements were performed at room temperature using combined Raman and scanning near field optical microscope (SNOM) WiTec Alpha 300 R equipped with 532 nm excitation laser source. Morphology of the synthesized powders was characterized by scanning electron microscopy performed with a Hitachi SU-70 field-emission scanning electron microscope (FE-SEM). Elemental analysis of the synthesized samples was performed by inductively coupled plasma optical emission spectrometry (ICP-OES) using Perkin-Elmer Optima 7000DV spectrometer. The samples were dissolved in 5% nitric acid ( $\text{HNO}_3$ , Rotipuran® Supra 69%, Carl Roth) and diluted to an appropriate volume. Calibration solutions were prepared by an appropriate dilution of the stock standard solutions (single-element ICP standards 1000 mg/L, Carl Roth).

### 3. Results and discussion

Washing of as-prepared precipitates is a commonly used procedure performing synthesis of inorganic materials by precipitation method. It is usually applied in order to remove remained dissolved ions from the reaction liquid phase and adsorbed ions from the surface of obtained precipitates. Deionized water is the most frequently used for these purposes. In the present work in addition to deionized water we took into consideration four other solvents (acetone, acetonitrile, ethanol and isopropanol). All these solvents are miscible with water. The polarities of AC, ACN, EtOH and i-PrOH are 0.355, 0.460, 0.654 and 0.546, respectively. Effect of the washing agent after drying procedure was visible even to the naked eye. The precipitates washed with  $\text{H}_2\text{O}$  and AC were compact in volume and densely agglomerated into few hard pieces, it was quite



difficult to grind them in an agate mortar. Visual appearance and mechanical properties of the precipitates washed with ACN, EtOH and i-PrOH were found to be strongly dependent on utilized amount of the solvent. The precipitates washed with higher amount of these liquids were voluminous and soft.

The XRD patterns of the as-prepared precipitates washed with 100 mL of different solvents and dried at 50 °C are given in Fig. 1. Phase composition analysis revealed that using H<sub>2</sub>O and AC as washing agents, crystalline phase corresponding to CDHA was obtained. Crystal phase composition was found to be independent of the used amount of H<sub>2</sub>O and AC. In the case of ACN, EtOH and i-PrOH different situation was observed. No sharp diffraction peaks were detected in the XRD patterns of these samples, only very broad peak at about 30°, which is characteristic for ACP [35]. It should be noticed that amorphous powders were obtained only using 100 mL and higher volume of the solvent, while CDHA was formed with lower amount of the solvent. The XRD patterns of the as-prepared powders washed with different amounts of solvent (20-100 mL) are shown in Fig. S1. The XRD results clearly illustrate the degradation of CDHA phase with increasing volumes of ACN, EtOH and i-PrOH.

Thermal decomposition behavior of the precipitated species washed with 100 mL of the solvent and dried at 50 °C is depicted in Fig. 2. It is obvious, that thermal behavior of the precipitates depends on the nature of the used washing agent and can be divided into 2 groups. The precipitates washed with H<sub>2</sub>O and AC, which reveal CDHA crystal phase, are combined in the first group. The TG curves of these samples are almost identical, only with the difference in a total weight loss. Initial mass loss up to 180 °C is associated with a removal of adsorbed solvents from the surface of the precipitates. This process further gradually continues by removal of crystallized water at higher

temperatures. The last weight loss at 765 °C is associated with final removal of water molecules from CDHA crystal lattice. With further temperature increase the sample mass becomes constant. Total mass loss for H<sub>2</sub>O- and AC-washed precipitates was only 7.3 and 9.5%, respectively, which is noticeably lower than for three other samples. The precipitates washed with ACN, EtOH and i-PrOH also exhibited very similar thermal behavior. The mass of the EtOH- and i-PrOH-washed precipitates did not change already starting from 400 °C. For ACN-washed sample thermal stability temperature is higher, however, weight loss above 400 °C is insignificant in comparison to the determined below this temperature. Total weight loss was 17.1, 22.5 and 19.7% for ACN-, EtOH- and i-PrOH-washed samples, respectively. This difference can be associated with amount of residual water removed from the samples at an initial stage of heating (below 160 °C). These results coincide with previously published work by Rodrigues and Lebugle [36]. The authors showed that as-prepared CPs synthesized in alcoholic medium contain almost 3 times higher amount of H<sub>2</sub>O in comparison to those synthesized in aqueous medium.

The XRD patterns of the precipitates washed with 100 mL of the solvent and annealed at 775 or 750 °C, are shown in Fig. 3. It is seen that in the case of H<sub>2</sub>O and AC, the powders after annealing at 775 °C crystallize to  $\beta$ -TCP phase. All diffraction peaks match very well the standard XRD data of rhombohedral Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> (ICDD 00-070-2065). And in the case of treatment with ACN, EtOH and i-PrOH the samples after annealing at 750 °C crystallize to  $\alpha$ -TCP polymorph. The XRD patterns of these samples match the standard XRD data of monoclinic Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> (ICDD 00-070-0364). The lattice parameters and crystallite size of the synthesized TCP polymorphs are summarized in Table 1. It is seen that the lattice parameters are very similar for each

group of the polymorphs. Average crystallite size was found to be smaller for  $\alpha$ -TCP samples and larger for  $\beta$ -TCP samples. Crystal structure of the final product was found to be independent of the volumes of H<sub>2</sub>O and AC used for washing procedure. The  $\beta$ -TCP phase was obtained after annealing in all cases. Oppositely, in the case of ACN, EtOH and i-PrOH crystal structure of the annealed products was found to be strongly dependent on the used amount of the solvent. The evolution of crystal phases depending on the amount of solvent used in the synthesis processing is illustrated in Fig. S2.

The initial idea of this study was to compare the products synthesized at exactly the same thermal conditions, however, it was not possible to do due to the formation of polymorphs mixtures.  $\alpha$ -TCP was found to be monophasic only at  $\leq 750$  °C, while at higher temperatures small amount of  $\beta$ -TCP phase was observed. On the other hand, the single-phase  $\beta$ -TCP polymorph was not obtained at 750 °C, since its CDHA precursor does not decompose completely at this temperature. Therefore, in order to prepare pure polymorphs, slightly different annealing temperatures were selected. In principal, identical temperature regime would not change the situation. The XRD patterns of the representative precipitates washed with H<sub>2</sub>O and EtOH and both annealed at 750 and 775 °C are shown in Fig. S3.

Vibrational spectroscopy was used for the characterization of the synthesized products in order to detect vibrations of possible amorphous species or crystalline phases, which might be hardly distinguished by XRD in presence of TCP. Fig. 4 shows FTIR spectra of the precipitates washed with 100 mL of the solvent and annealed at 775 or 750 °C. To demonstrate the vibrational modes characteristic of the phosphate group the wavenumber range of 1500–400 cm<sup>-1</sup> was selected. The FTIR spectra of the samples washed with H<sub>2</sub>O and AC and annealed at 775 °C reveal the presence of characteristic

phosphate absorption bands observed at 1150–990 ( $\nu_3$ ), 971 and 944 ( $\nu_1$ ), at 605, 590 and 544 ( $\nu_4$ ), and at 433  $\text{cm}^{-1}$  ( $\nu_2$ ). The obtained results confirm the formation of  $\beta$ -TCP as the main crystalline phase. For the samples treated with 100 mL of ACN, EtOH and i-PrOH and annealed at 750 °C absorption bands located at 1145–975 ( $\nu_3$ ), 957 ( $\nu_1$ ), at 550, 561, 582, 595 and 611 ( $\nu_4$ ), and 452  $\text{cm}^{-1}$  ( $\nu_2$ ) can be observed in FTIR spectra, which clearly demonstrate formation of  $\alpha$ -TCP polymorph [11]. These observations are consistent very well with the XRD results. There are also weak absorption bands at 1213  $\text{cm}^{-1}$  and 729  $\text{cm}^{-1}$  which could be attributed to the presence of negligible amount of  $\text{P}_2\text{O}_7^{4-}$  groups in the synthesis products [37]. Formation of calcium pyrophosphate as a by-product is quite frequently observed for TCP powders synthesized by precipitation method [16, 38]. The FTIR spectra obtained for the precipitates washed with 20–80 mL of ACN, EtOH and i-PrOH and annealed at 750 °C additionally to phosphate bands have an additional well resolved band at 877  $\text{cm}^{-1}$  (see Fig. S4). This band corresponds to P–O(H) stretching in monohydrogenophosphate ions ( $\text{HPO}_4^{2-}$ ) [39]. It is also noteworthy that after washing with 100 mL the characteristic  $\text{HPO}_4^{2-}$  absorption band disappears from FTIR spectrum. Contrary, the intensity of the absorption band attributed to pyrophosphate group increases.

Fig. 5 presents Raman spectra in a wavenumber region from 300 to 1500  $\text{cm}^{-1}$  for the precipitates washed with 100 mL of the solvent and annealed at 775 or 750 °C. These spectra confirm the results obtained by XRD and FTIR measurements. All Raman spectra contain peaks characteristic to the internal vibrations of phosphate groups in TCP. On the other hand, the spectroscopic differences between two groups of the samples corresponding to different TCP polymorphs are clearly seen. The spectra of the samples washed with  $\text{H}_2\text{O}$  and AC are dominated by two distinctive sharp peaks located

at around 955 and 977  $\text{cm}^{-1}$ , which are attributed to the symmetric stretching ( $\nu_1$ ) of P–O bonds in tetrahedron. Asymmetric stretching mode ( $\nu_3$ ) of P–O bonds can be seen in spectra as less intense bands in the range of 1010–1130  $\text{cm}^{-1}$ . Two other groups of the bands can be observed at lower wavenumbers from approximately 395 to 510  $\text{cm}^{-1}$  and from 540 to 660  $\text{cm}^{-1}$  and could be assigned to  $\nu_2$  and  $\nu_4$  O–P–O bending deformations of the phosphate tetrahedron, respectively [40, 41]. For the samples washed with ACN, EtOH and i-PrOH, the most intense bands specific of  $\beta$ -TCP are replaced by a single band at 965  $\text{cm}^{-1}$  attributed to  $\nu_1$  vibration mode of phosphate groups of  $\alpha$ -TCP. Other observed bands ( $\nu_2$ ,  $\nu_3$  and  $\nu_4$ ) in the Raman spectra of these samples also have different shape in comparison to those of  $\beta$ -TCP, but positions stay nearly the same. However bands attributed to  $\nu_3$  mode are quite weak in the spectra of  $\alpha$ -TCP [42, 43].

The SEM micrographs of  $\beta$ - and  $\alpha$ -TCP samples, synthesized using  $\text{H}_2\text{O}$  and ACN, respectively, are given in Fig. 6 as representative. The SEM images demonstrate that synthesized TCP powders exhibit slightly different morphological features depending on their crystal structure. The sample washed only with  $\text{H}_2\text{O}$  (Fig. 6a) consist of approximately 200–500 nm sized nearly spherical particles, which are necked to aggregates of irregular shape. In the case of AC (Fig. S5a) morphology of the powders is similar, particles have comparable size, but more polydisperse and show higher coalescence in comparison to  $\text{H}_2\text{O}$ -washed. The  $\alpha$ -TCP sample synthesized after ACN treatment (Fig. 6b) consists of very uniform thinner particles with prolonged irregular shape. The thickness of the particles is about 300 nm. Powders synthesized with EtOH and i-PrOH in their turn show very similar morphological features (Fig. S5b,c). However, it can be seen that EtOH-washed powders are slightly larger in size.

Elemental analysis of the synthesized products was performed in order to check possible selective removal of calcium or phosphate ions from the precipitates by certain liquid during washing procedure. The results of the determination of Ca and P by ICP-OES in the samples washed with 100 mL of the solvents are summarized in Table 2. As seen from Table 2, the determined Ca to P ratio for all samples was slightly lower than nominal one. However, the results obtained for different solvents were very close to each other. As a rule, authors do not report on the chemical composition of TCP powders in their works, therefore it is difficult to compare the obtained results with literature data. However, previously Torres *et al.* [38] reported on the chemical composition of synthesized Mn-doped  $\beta$ -TCP. The ratio of metals to P in this study was determined to be in the range from 1.494 to 1.482, which is also lower than theoretical for TCP. Stahli *et al.* determined Ca/P ratio 1.44 in hydrogen-substituted  $\beta$ -TCP synthesized in organic media [44]. The same tendency caused by the same reason could be expected for our synthesized samples. Moreover, the results presented in Table 2 correlate with the results documented in previous paragraphs, which confirm the presence of  $\text{Ca}_2\text{P}_2\text{O}_7$  as a minor phase in the synthesized TCP specimens. Ca to P ratio in this by-product is 1 to 1, which slightly distorts elemental ratio in bulk material. The results of elemental analysis show that formation of the crystalline or amorphous as-prepared precipitates is not induced by the difference in chemical composition.

It can be concluded that after the heat treatment at nearly identical conditions the precipitated CDHA and ACP precursors crystallize to  $\beta$ -TCP and  $\alpha$ -TCP, respectively. Thereby, the reason of the formation of different polymorphs of TCP probably lies in the initial stage of the synthesis, i.e. in the formation of CDHA or ACP after washing and drying procedures. Possible explanation may be found in the interaction of  $\text{H}_2\text{O}$

molecules with as-precipitated species. During the precipitation of CP, an amorphous material built up of clusters forms first. These clusters are composed of CPs in which ions are highly solvated, interacting and forming a gel [45]. The presence of H<sub>2</sub>O in the reaction medium leads to the formation of hydration layer around CP particles, strong interaction between H<sub>2</sub>O molecules and phosphates, and, subsequently, formation of denser CDHA structure. Bonding of ACN, EtOH and i-PrOH to H<sub>2</sub>O molecules modifies water interaction with phosphates, and CP clusters become partly isolated from each other. Consequently, the process of agglomeration of clusters is interrupted and the level of hydrolysis is reduced. Taking into account that transformation of ACP to CDHA occurs by a dissolution/reprecipitation process [46], the effect of the solvents can be attributed to the fact that ACN, EtOH and i-PrOH decrease solubility and dissolution rate of ACP, resulting in the decrease of CDHA formation. Moreover, ACN, EtOH and i-PrOH in the filtered wet solid expedite the drying process and slow the transformation of ACP [45-48]. However, to obtain single-phase  $\beta$ -TCP and  $\alpha$ -TCP, the temperature of final heat-treatment should be also adjusted. Finally, the developed environmentally benign synthetic approach for  $\alpha$ - and  $\beta$ -TCP could be successfully applied for modification of surface of bone implants through wet chemistry approach [49, 50].

#### **4. Conclusions**

In the present work effects of processing conditions on the synthesis of TCP polymorphs were investigated.  $\alpha$ - and  $\beta$ -TCP polymorphs were prepared by the same wet precipitation procedure at very close thermal conditions. Formation of the desired TCP polymorph can be controlled by applying a washing procedure to as-prepared

calcium phosphate precipitates. It was shown that the nature and amount of washing agent determine amorphous or crystalline nature of the as-precipitated species and the formation of TCP polymorphs during the thermal treatment. Washing of the as-prepared precipitates with water and acetone led to the formation of  $\beta$ -TCP, while washing with acetonitrile, ethanol and isopropanol led to the crystallization of  $\alpha$ -TCP. Maximal temperature for the synthesis of pure  $\alpha$ -TCP under chosen synthesis conditions was determined to be 750 °C with the following formation of minor  $\beta$ -TCP phase at higher temperatures. On the contrary, minimal temperature for the synthesis of pure  $\beta$ -TCP was determined to be only 775 °C. The SEM images demonstrated that synthesized TCP powders exhibited slightly different morphological features depending on their crystal structure.

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**Figure captions**

**Fig. 1.** XRD patterns of the as-prepared precipitates washed with 100 mL of the solvent and dried at 50 °C.

**Fig. 2.** TG/DTG curves of the as-prepared precipitates washed with 100 mL of the solvent and dried at 50 °C.

**Fig. 3.** XRD patterns of the precipitates washed with 100 mL of different solvent and annealed at 775 °C (H<sub>2</sub>O and AC) or 750 °C (ACN, EtOH and i-PrOH).

**Fig. 4.** FTIR spectra of the precipitates washed with 100 mL of the solvent and annealed at 775 °C (H<sub>2</sub>O and AC) or 750 °C (ACN, EtOH and i-PrOH).

**Fig. 5.** Raman spectra of the precipitates washed with 100 mL of the solvent and annealed at 775 °C (H<sub>2</sub>O and AC) or 750 °C (ACN, EtOH and i-PrOH).

**Fig. 6.** SEM micrographs of the precipitates washed with 100 mL of H<sub>2</sub>O (a) and ACN (b) and annealed at 775 and 750 °C, respectively.

**Table 1.** Lattice parameters and crystallite size of the synthesized TCP samples.

Sample	a, Å	b, Å	c, Å	V, Å <sup>3</sup>	Crystallite size, nm
TCP-H <sub>2</sub> O	10.423	10.423	37.336	3512	59.7
TCP-AC	10.426	10.426	37.336	3514	62.9
TCP-ACN	12.857	27.222	15.187	4290	46.0
TCP-EtOH	12.860	27.227	15.191	4293	45.4
TCP-i-PrOH	12.861	27.226	15.190	4293	49.7

**Table 2.** Results of elemental analysis of the synthesized products.

Sample	Ca to P ratio
TCP-H <sub>2</sub> O	1.48
TCP-AC	1.46
TCP-ACN	1.46
TCP-EtOH	1.47
TCP-i-PrOH	1.45

