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Preparation and characterization of biphasic calcium phosphate ceramics of desired composition

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Abstract A modified processing route for fabricating dense and porous biphasic calcium phosphate (BCP) ceramics of desired and reproducible phase composition (hydroxyapatite (HA)/β-tricalcium phosphate (β-TCP) ratio) has been developed. The principal idea of the route was combining a precipitation and a solid phase methods. First, a nonstoichiometric (slightly carbonated calcium-deficient) HA (CdHA) precipitate was synthesized by mixing a calcium carbonate ($CaCO_3$) water suspension with an orthophosphoric acid (H_3PO_4) solution in abundance (related to the amount resulting in a stoichiometric HA) under definite conditions, and a powder of the precipitate was prepared and calcinated in air (860°C, 1.5 h). In the second stage, a BCP ceramics of the composition determined by the calcium-deficiency in a calcinated powder (the acid abundance in a mixture) was processed by sintering powder compacts with or without a porosizer under appropriate conditions (1,200°C, 2h). A calibrating dependence of the HA/β-TCP ratio in the ceramics on the acid abundance has been plotted which enabled a controlled preparation of BCP ceramics. A correlation based on unresolved bands in v_4-PO_4^{3-} domain in IR-spectra of nanostructured BCP materials was found. Using the correlation, the process of CdHA → β-TCP transformation could be easily monitored. The density and microhardness of the BCP ceramics neglectly depended on the composition, however, the compressive strength did: the lower the HA/β-TCP ratio, the higher the strength in the dense materials.

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1 Introduction

Biphasic calcium phosphate (BCP) ceramics are intimate mixtures of hydroxyapatite (HA), $Ca_{10}(PO_4)_6(OH)_2$, and β-tricalcium phosphate (β-TCP), $Ca_3(PO_4)_2$ crystals of varying phase compositions (HA/β-TCP ratios). They have found numerous medical applications, mainly as bone graft substitute in stomatology and orthopedics [1, 2].

To process a BCP material, a synthetic, natural or biological calcium-deficient apatite (CDA) is sintered at a temperature above 700°C. The extent of calcium deficiency (Ca/P molar ratio < 1.67) determines the HA/β-TCP ratio in the BCP ceramics. The HA/β-TCP ratio, in its turn, affects the reactivity of the material: usually, the lower the ratio, the higher the reactivity (expressed in vitro as the extent of dissolution in an acid buffer). However, the reactivity also depends on particle size, and micro- and macroporosity of the BCP that are affected by temperature and duration of sintering as well as by other variables of processing.

Since some of the variables are hard to control, BCP materials have often exhibited different and even contradictory functional characteristics (such as phase composition, mechanical properties, dissolution, rate of new bone formation, etc.). For example, the compressive strength was found to decrease as the Ca/P ratio decreased in BCP ceramics [3]. However, according to another study [4], the mechanical characteristics were getting better when the relative amount of β-TCP increased in BCP ceramics prepared under conditions that seemed to be the same. BCP ceramics processed of a single CDA phase had higher compressive strength and lower extent of dissolution compared to BCP ceramics prepared by mixing two unsintered calcium phosphates one of which transformed after sintering to HA, and the other—to β-TCP [5, 6]. In some cases, BCP ceramics with similar HA/β-TCP ratios manifested different dissolution properties [2]. This is considered to be caused by different crystal size and micro- and macroporosities in the materials. These characteristics could influence the extent of dissolution both in vitro and in vivo: the greater the porosity and the lower the crystal size, the higher the extent of BCP dissolution [2, 7]. Although the rate of biodegradation depended on the method of preparation, the rate of new bone formation was not significantly different for BCP ceramics. Thus, the BCP with the HA/β-TCP ratio of 20/80 was the most effective in eliciting a greater bone formation; however, the BCP with the ratio of 80/20 showed the best result in repairing surgically created periodontal defects [2, 5].

The intermediate product in conventional BCP processing is a CDA produced by a precipitation method [2]. Though this way is not novel, wet synthesis of CDA's of a given Ca/P ratio has not been easy until now since the degree of nonstoichiometry depends on a number of processing variables. To govern the process, effective crystallization sets were proposed for controlling and monitoring the principal reaction parameters (such as solution composition and supersaturation, temperature, pH, stirrer speed, duration, aging time, etc.,) [8, 9]. However, in case of industrial production, simple processing routes are still of value because of commercial reasons.

A variable which is particularly hard to control is the impurities. In the precipitation based on the reaction of $Ca(NO_3)_2$ and $(NH_4)_2HPO_4$ solutions [2], impurities greatly (and often unclearly) affected the physical–chemical and, consequently, the functional characteristics of the products [2, 10]. In an other conventional CDA's processing employing the reaction of $Ca(OH)_2$ suspension and H_3PO_4 solution [11], the storage of the initial reactants usually led to absorption of atmospheric CO_2 by $Ca(OH)_2$ and its partial transformation to $CaCO_3$. Presence of the last resulted in errors in preparation of appropriate amounts of the reactants and, consequently, in irreproducibility of BCP characteristics. Hence, it makes sense to use $CaCO_3$ (due to its chemical stability in storage at standard conditions) instead of $Ca(OH)_2$ in this reaction.

An X-ray diffraction method is usually employed for phase characterization in BCP's [2]. However, the method is time-consuming by itself and, besides, involves a calibrating dependence of peak intensities versus phase compositions which should be plotted before and is a complicated procedure. We earlier paid attention to the fact that appearance of some β-TCP in a CDA during heat treatment was, in particular, associated with changes in ν_4-PO_4^{3-} absorbances in corresponding IR-spectrum, and this was thought to become an additional and more simple way (compared to the XRD-route) in phase characterization of BCP's.

Hence, the aim of this study was to develop a modified simple processing for preparation of BCP ceramics of given phase composition and an IR-spectroscopical way for evalution of HA/β-TCP ratio in the ceramics.

2 Materials and methods

2.1 Preparation of calcium-deficient apatites and corresponding BCP ceramics

The developed processing route resulted from combination of a precipitation and solid-phase methods. As is known, when under definite conditions, calcium carbonate, $CaCO_3$, and orthophosphoric acid, H_3PO_4, are mixed in proportion giving Ca/P ratio = 1.67 (the stoichiometric value of HA) and a precipitate obtained is heated to high temperatures, HA forms; deviation from the stoichiometric proportion results in a product with Ca/P ratio different from that of HA [12]. Consequently, some abundance in the acid related to the "stoichiometric" amount in the stage of synthesis will result in a BCP product after sintering. In this case, the following reactions occur during the process:

$$\begin{aligned}&(5-2x)\mathrm{CaCO_3} + (3-x)\mathrm{H_3PO_4} \rightarrow \text{HA based precipitate}\\&\quad\rightarrow (1-x)\mathrm{Ca_5(PO_4)_3OH} + x\mathrm{Ca_3(PO_4)_2} + (4-x)\mathrm{H_2O}\\&\qquad + (5-2x)\mathrm{CO_2}\end{aligned}$$

where x is the part of β-TCP in a final product.

Precipitates were prepared by fast mixing a water suspension of $CaCO_3$ with a H_3PO_4 water solution (both initial reactants were reagent grade) followed by durable, for 24 h, mixing the reaction medium in a magnetic mill until neutral pH value was achieved in the medium. A precipitate formed was centrifugalized, dried in an oven at 90°C and sifted through a 100-μm sieve. Six types of powders were prepared in such a way, for which the acid abundance was 1, 3, 5, 7, 10 and 12 wt.%, respectively, and a stoichiometric HA powder was also prepared (no acid abundance). The powders were calcinated at 860°C for 1.5 h. Compacts of the calcinated powders were prepared in a disk form (3 mm height and 8 mm diameter) by uniaxial pressing under 100 MPa without or with preliminary adding cellular polystyrene as porosizer [10]. All the compacts were sintered at 1,200°C for 2 h in wet atmosphere since these variables were found to be optimal for preparing "dense" (i.e., containing only slight microporosity) or porous (the porosity depended on the amount of porosizer added) ceramics [11].

2.2 Characterization of samples

Phase composition and microstructure of samples were studied by X-ray diffraction (XRD; X-ray diffractometer, Philips, model APDW40C, Cu K_{α}), infrared spectroscopy (IR; Perkin-Elmer 1720X, pellets of a 300 mg KBr/1 mg sample were prepared and examined ($400\ \mathrm{cm}^{-1} < \lambda < 4{,}000\ \mathrm{cm}^{-1}$) in the transmittance mode with 4-cm^{-1} resolution), and scanning electron microscopy (SEM; LEO Gemini 1530, gold-sputtered samples). These methods were used to characterize samples before, in the process, and after heat treatments. Phase composition in a BCP was evaluated by comparing the ratio of intensities for most intense diffraction peaks of the two phases with those in a calibrating dependence obtained for standard mixtures of pure HA and β-TCP [13]. The estimated error of the found HA/β-TCP ratio was less than 1 wt.%. Microhardness was measured according to DIN 50359-1 at room temperature using a Fischerscope® tester H100VP XY-Prog with a Vickers square pyramidal diamond indenter at a load of 0.002 N. The relative porosity of samples was calculated from the formula $\eta = (\rho - \rho_{\mathrm{T}})/\rho_{\mathrm{T}}$ using a measured ρ value and the theoretical one $\rho_{\mathrm{T}} = 3.167\ \mathrm{g\ cm}^{-3}$. Mechanical testing was conducted on an Instron-type machine with a displacement control adjusted to 0.2 mm/min. Compressive strength σ_{c} was derived from a load-deformation curve using the formula:

$$\sigma_{\mathrm{c}}(\mathrm{Pa}) = F_{\mathrm{c}}(\mathrm{N})/\mathrm{S}(\mathrm{m}^2),$$

where F_{c} was the force applied to the disk surface, S.

3 Results and discussion

3.1 Diagram of the phase composition

The X-ray diffractograms and IR-spectra of the ceramics sintered of the compacts for which the acid abundance in the stage of precipitation was 0, 5, 7 and 12 wt.%, respectively, are shown in Figs. 1 and 2. It can be clearly seen, that the phase composition in the ceramics changed from HA only (Figs. 1a and 2a) in the case of stoichiometric proportion of the reactants (0 wt.% abundance of H_3PO_4) to β-TCP only (Figs. 1d and 2d) for the 12 wt.% acid abundance. BCP's were found in the ceramics which corresponded to intermediate values of acid abundance. A diffractogram or an IR-spectrum of a BCP ceramics was a superposition of single diffractograms or spectra of HA and (plus) β-TCP. The characteristic diffraction peaks or absorption bands of pure HA and β-TCP were present in them (e.g., Figs. 1c and 2c).

A diagram of the phase composition in the ceramics versus the acid abundance was only plotted from XRD data, calculated using the method described in [13] (Fig. 3).

Numerous examinations have proved that, using the diagram, BCP ceramics of any desired composition could

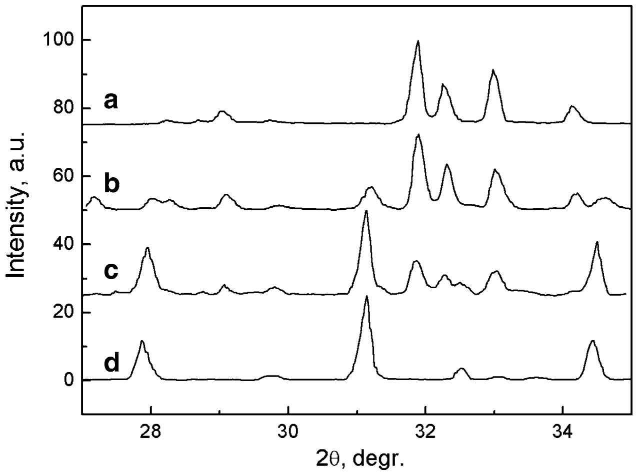

Fig. 1 Diffractograms of the ceramics sintered from the powders prepared at the acid abundance of (a) 0 wt.%, (b) 5 wt.%, (c) 7 wt.%, and (d) 12 wt.%

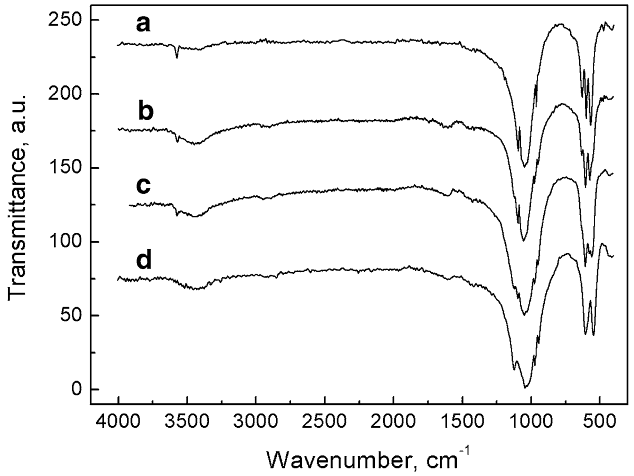

Fig. 2 IR-spectra of the ceramics of: (a) HA, (b) 65 HA/35 β-TCP, (c) 35 HA/65 β-TCP, and (d) β-TCP. The corresponding XRD profiles are Figs. 1a–d, respectively

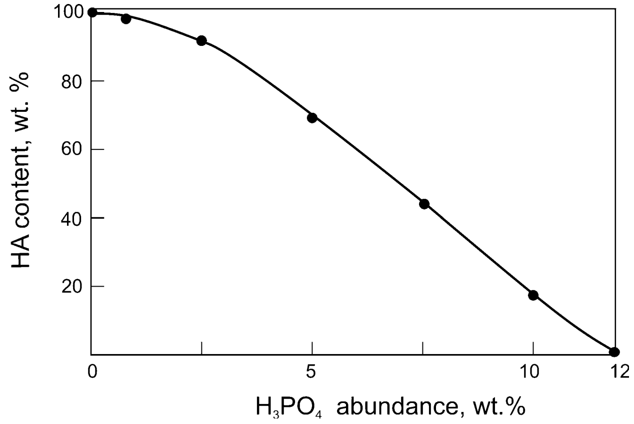

Fig. 3 Diagram of the ceramics composition versus the acid abundance in the stage of synthesis

be reproducibly prepared (the deviation in HA/β-TCP ratio was less than ±3 wt.%).

3.2 Process of the phase formation

Two kinds of compacts were studied in order to reveal the conditions under which a final composition in ceramics was formed: BCP ceramics of 50% HA/50% β-TCP resulted at high temperatures from the one (the acid abundance was 6 wt.%), and β-TCP ceramics—from the other (the acid abundance—12 wt.%). Ten samples of each kind were prepared of noncalcinated powders. The samples were gradually heated with a step of 100°C and 30 min dwell-time at each temperature in the range of 600–1,200°C.

The diffractograms and IR-spectra of the samples, from which the BCP ceramics was finally formed, are presented in Figs. 4 and 5. The samples consisted of a slightly carbonated calcium-deficient HA (CdHA) upon annealing at 600°C. This resulted from the absence of any distinct reflexions except those of HA in the diffractogram (Fig. 4a), and the presence of weak absorbances in 1,400–1,600 cm^{-1} range and at about 875 cm^{-1} in the IR-spectrum (Fig. 5a) attributed to CO_3^{2-}—carbonate group. Perfection of the structure due to solid phase synthesis of the CdHA followed by its partial transformation into β-TCP happened at temperatures above 600°C. Annealing the compacts in humid atmosphere led to loss of the carbonate groups and appearance of OH^- ions in the lattice at 800°C. The relevant IR-spectrum (Fig. 5b) showed considerable decrease in intensities of CO_3^{2-} absorbances in 1,400–1,600 cm^{-1} range and noticeable intensification of both the OH^- peaks at about 3,570 (ν_S-OH^-) and 630 cm^{-1} (ν_L-OH^-). Some portion of β-TCP also appeared in the sample and the amount increased as the annealing temperature increased. Finally, a BCP (50% HA/50% β-TCP) formed at 1,000°C: the characteristic HA and β-TCP diffraction peaks and absorbances were clearly seen in Figs. 4d and 5d, respectively. During the transformation process, the intensities of β-TCP reflections and absorbances (e.g., at about 945 and 1,130 cm^{-1}) gradually increased simultaneously with decreasing intensities of CdHA ones.

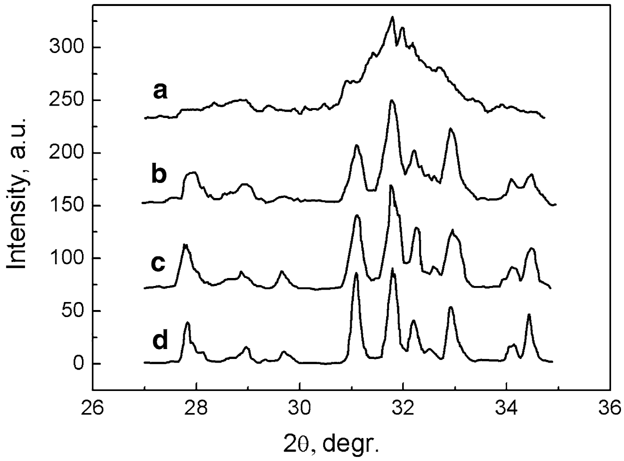

Fig. 4 Diffractograms of the samples, from which BCP ceramics (50 HA/50 β-TCP) was finally obtained, after annealing at: (**a**) 600°C, (**b**) 800°C, (**c**) 900°C, and (**d**) 1,000°C. Corresponding compositions: (**a**) CdHA, (**b**) 80 HA/20 β-TCP, (**c**) 60 HA/40 β-TCP, and (**d**) 50 HA/50 β-TCP

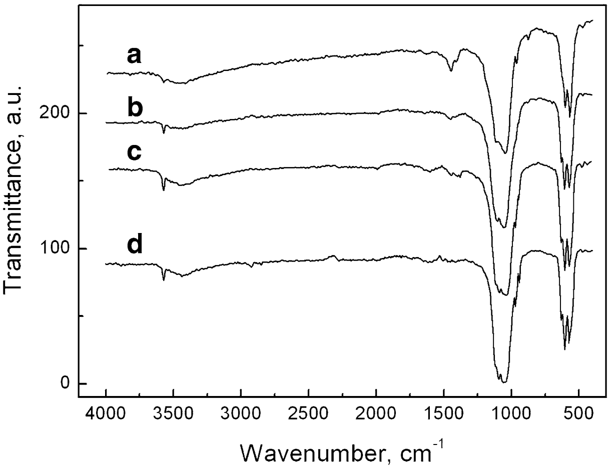

Fig. 5 IR-spectra of the samples which diffractograms are Figs. 4a–d

The results shown in Figs. 4 and 5 exhibited that the process of phase formation occurred not at a definite temperature but in a wide temperature range. To more detail the process, the dependence of a distance, ΔK, between two absorption peaks in 520–660 cm^{-1} range of the ν_4 bending mode of PO_4^{3-} ions versus heating temperature was measured (Fig. 6) using the other batch of samples that finally resulted in β-TCP ceramics. The

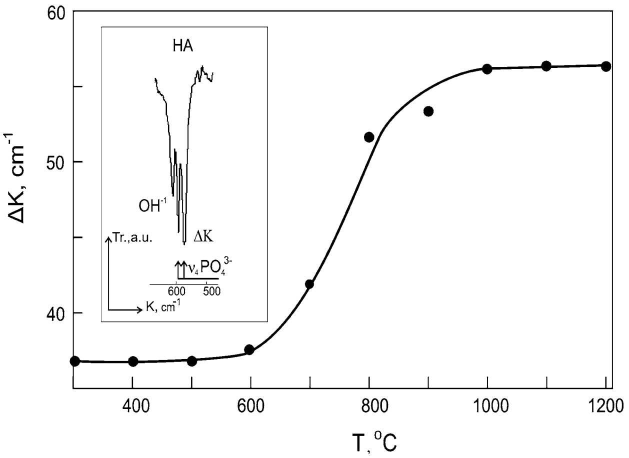

Fig. 6 ΔK value in IR-spectrum versus annealing temperature for the CdHA sample with acid abundance of 12 wt.%. The inset explains the determination of the ΔK value

distance manifested no change (within the experimental error of ±4 cm^{-1}) in 300–600°C annealing range and corresponded to that in the IR-spectrum of a CdHA (Figs. 6 and 5a). On the other hand, the distance did not change any more in the annealing range of 1,000–1,200°C and corresponded to that in the absorption spectrum of pure β-TCP (Figs. 6 and 2d). A gradual increase in ΔK value from that of CdHA to that of β-TCP was revealed in the temperature range of 600–1,000°C. This additionally and more preciously exhibited the transformation of the CdHA into the β-TCP through a BCP phase of changing composition.

A dependence similar to that in Fig. 6 was also plotted for the process of CdHA transformation into 50 HA/50 β-TCP ceramics for the first kind of samples. The two dependences showed that the phase composition in the ceramics neglectly depended on higher temperatures of 1,000–1,200°C for 2 h sintering (e.g., see the plateau in Fig. 6).

The process of phase transformation was associated with morphology change of powder particles. It was particularly seen in the case of final β-TCP formation in the ceramics (Fig. 7). The particles mainly had an elongated form up to 600°C (Fig. 7a). However, they altered in the 600–1,000°C firing range: some “hands” and “legs” grew at the particles (Fig. 7b), and the altered particles disintegrated into roundish pieces at 1,000°C (Fig. 7c).

Though the phase composition formed in the samples at 1,000°C changed minor upon annealing at higher temperatures (within 1,000–1,200°C) according to XRD-data and ΔK-dependences, IR-spectra of the samples still slightly differed. The v_4-PO_4^{3-} region turned out to be of special interest. The v_4-PO_4^{3-} absorbance appeared as a sharp doublet at about 600 and 570 cm^{-1} for HA, and the localization of the peaks could differ by a few cm in the case of a CdHA [14–16]. The values found for the doublet from spectra in Figs. 2a and 5a were in fine agreement with these data. The complete or partial transformation of a CdHA into β-TCP or BCP were manifested in Figs. 2d or 5d as a slight broadening and shift of the 600 cm^{-1} band to the higher wave numbers (up to 610–615 cm^{-1}). The other peak of the doublet underwent a splitting into 570 cm^{-1} band itself and an adjacent 550 cm^{-1} one. It was found that the more the relative amount of β-TCP in a sample (the less the HA/β-TCP ratio) the higher the intensity of the novel 550 cm^{-1} band and the weaker the intensity of the 570 cm^{-1} peak. Finally, e.g., for pure β-TCP, the v_4-PO_4^{3-} mode consisted of a broadened band at 605–615 cm^{-1} and a sharper one at 550–560 cm^{-1} (Fig. 2). Consequently, the characteristics of the 570 cm^{-1} band displayed the presence and decrease in quantity of a CdHA and those of the 550 cm^{-1} band—an accompanied appearance and increase in relative amount of β-TCP in a BCP material during heat treatment. Simultaneously, as mentioned, the 600 cm^{-1} band just appeared to be shifted by a few cm to the higher values.

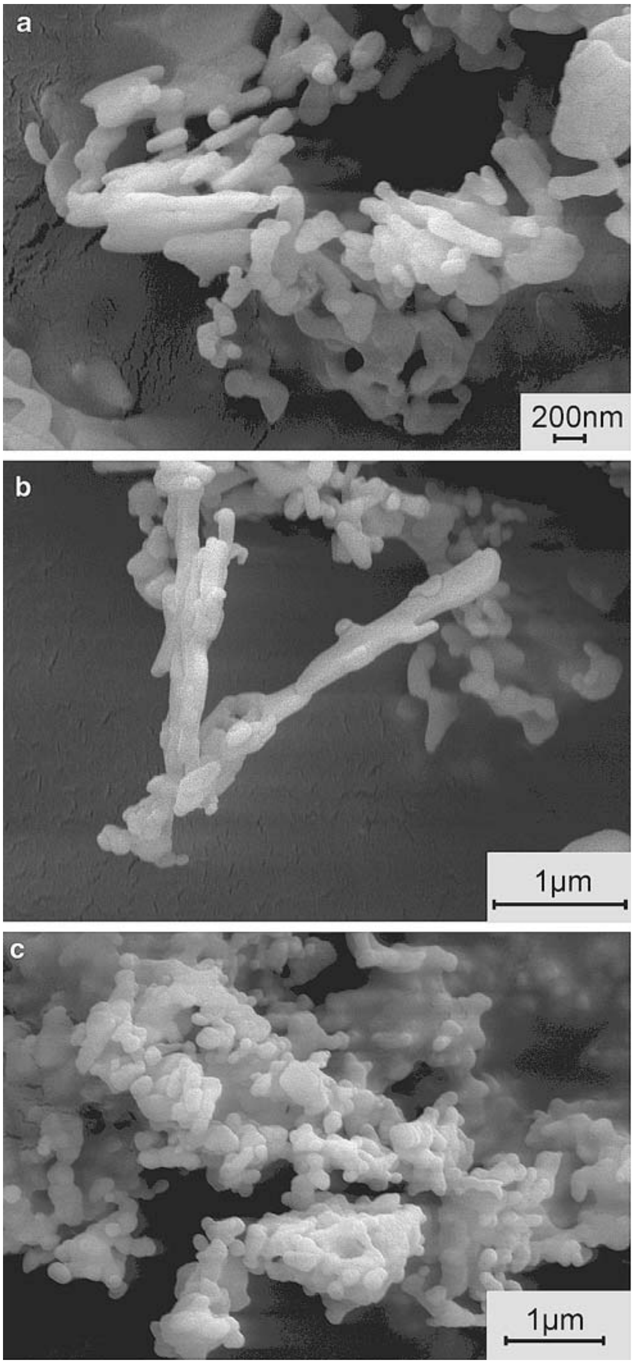

Fig. 7 Morphology alterations of the particles in the powder intended for obtaining β-TCP ceramics and annealed at: (**a**) 600°C, (**b**) 800°C, and (**c**) 1,000°C

One was supposed that the picture for the 600 cm^{-1} band really was like that for the 570 cm^{-1} absorbance: a band at about 610 cm^{-1} could appear and intensify in a spectrum with increasing relative β-TCP content in a BCP ceramics. To check this supposition, a spectrum of higher resolution was obtained of a ceramics, seemed to be β-TCP, however, sintered at a little lower temperature of 1,150°C (than 1,200°C in all other cases). To enhance the resolution, the recording was conducted at twice higher tape rate as usually. It was found that the v_4-PO_4^{3-} bands actually had some additional features (Fig. 8a). As expected, besides the two main β-TCP bands at 615 and 558 cm^{-1}, two shoulders at 594 and 573 cm^{-1} were clearly seen which indicated some traces of CdHA to remain in the ceramics though both XRD data and IR spectrum at usual recording rate (Fig. 8b) only displayed β-TCP. Thus, the slight broadening and shift of the 600 cm^{-1} band was due to superimposition of two unresolved bands of CdHA and β-TCP. The less the HA/β-TCP ratio in the ceramics the sharper and further moved to the higher wave numbers of the unresolved band. This could be an explanation why this band in the v_4-PO_4^{3-} doublet of β-TCP was found at from 600 cm^{-1} up to 630 cm^{-1} [14–16].

Though the high temperature annealing resulted in minor changes in phase composition at temperatures higher than 1,000°C, grain growth happened in ceramics: dense grains of micron sizes formed (Fig. 9) of the loose agglomerates of submicron particles (Fig. 7c). Considering this, the above results could be additionally elucidated. Due to the grain growth, the diffraction peaks in Fig. 1 were sharper than those in Fig. 4 (a unit of the 2θ scale in Fig. 1 is larger than that in Fig. 4) since the submicron size crystallites caused broadening the diffraction maxima. The PO_4^{3-} bands in IR-spectra of materials based on HA also broaden with decreasing crystallinity [17]. Consequently, the 570 cm^{-1} peak of CdHA and the 555 cm^{-1} peak of β-TCP were united because of broadening and appeared as one not to mention the other doublet in v_4-PO_4^{3-} region having much smaller difference in wave numbers. As a result, the gradual increase of relative β-TCP amount in the samples caused the intensification of β-TCP bands in the 570 and 555 cm^{-1} (β-TCP) doublet as well as in the 610 (β-TCP) and 600 cm^{-1} doublet with respect to the adjacent CdHA peaks. Since both of the doublets were not resolved because of submicron grains in the noncalcinated samples, the intensification led to shifting the doublets as two single bands to opposite directions in the v-scale. This departure of the peaks from each other resulted in the ΔK-dependence in Fig. 6.

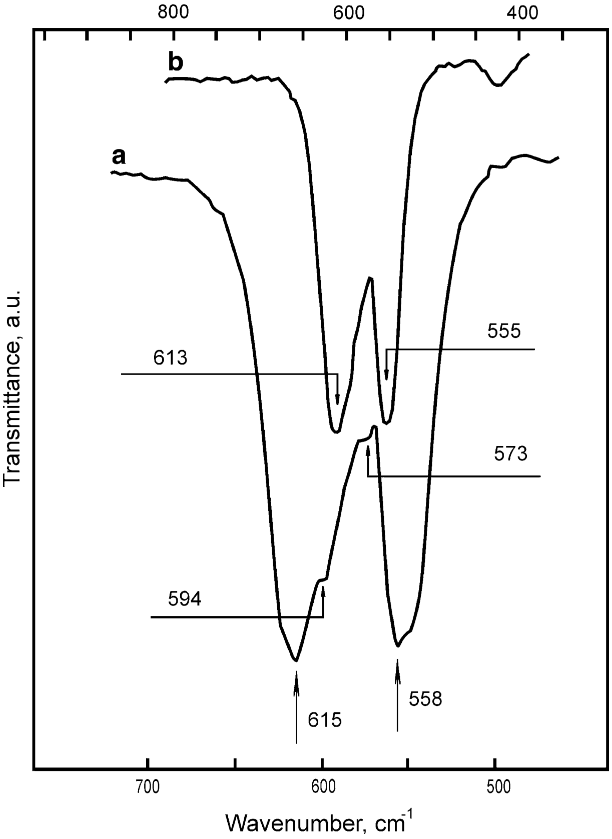

Fig. 8 v_4-PO_4^{3-} mode in spectra of a β-TCP with some traces of HA at: (**a**) twice higher recording rate (45 mm/min) and (**b**) usual one (22.5 mm/min)

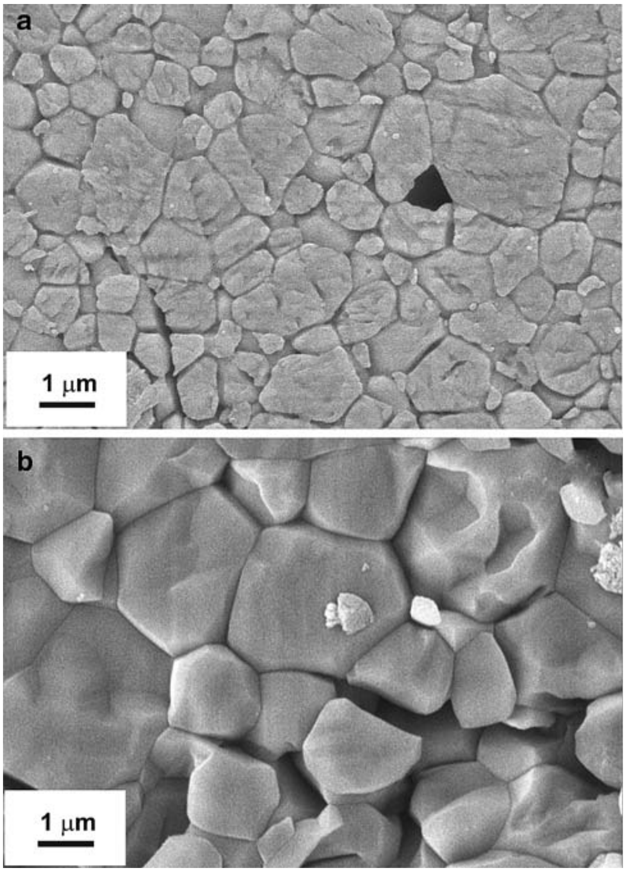

Fig. 9 Microstructure of HA (**a**) and β-TCP and (**b**) ceramics sintered at 1,200°C

In the above consideration, there is nothing on the third band at about 628–635 cm^{-1} in the v_4-PO_4^{3-} mode of a CdHA [15, 16]. The point is the band coincided with librational frequency of OH^- ions at about 630 cm^{-1} and practically could not be resolved. In addition, both of them

Table 1 Density (ρ), microhardness (H_V) and compressive strength (σ_c) of the dense ceramics

HA content (%)	ρ (g/cm^3)	H_V (MPa)	σ_c (MPa)
0	2.96 ± 0.01	590 ± 47	606 ± 61
26	3.01 ± 0.01	596 ± 48	591 ± 59
47	2.99 ± 0.01	608 ± 49	575 ± 58
73	2.99 ± 0.01	658 ± 53	544 ± 54
91	2.98 ± 0.01	697 ± 56	508 ± 51
96	3.01 ± 0.01	610 ± 49	420 ± 42
100	3.05 ± 0.01	668 ± 53	373 ± 37

were of weak intensities and progressively weakened during the thermal transformation of a CdHA.

3.3 Mechanical properties of the ceramics with various compositions

Compressive strength and Vickers microhardness were measured in dense and porous ceramics. The averages of the values were obtained for 10 samples of the two kinds of ceramics (five measurements for each sample).

The compressive strength of the dense (3–6% microporosity) BCP ceramics became higher as the β-TCP content increased (Table 1). The density in the ceramics slightly depended on phase composition. This accounted for minor effect of the composition on microhardness since the last is known to be highly influenced by density in calcium-phosphate ceramics [12, 18]. The average grain sizes in ceramics of various compositions were comparable (Fig. 9) and, like the density (and microhardness), were mainly determined by sintering temperature. Hence, the strengthening clearly observed in the BCP-ceramics was associated with increasing amount of β-TCP.

The compressive strength in the macroporous ceramics of HA, β-TCP and 60 HA/40 β-TCP ratio was found versus their porosity. The β-TCP ceramics also manifested better strength characteristics than those in HA ceramics. The BCP ceramics showed intermediate values of the compressive strength. Understanding the nature of these correlations needs additional data, particularly porosity characteristics (pore size and shape, distribution, interconnectivity, etc.,). A relevant study is in progress.

4 Conclusions

A modified processing route for fabrication of porous and dense BCP ceramics of desired composition has been developed. The route consisted of preparation of slightly carbonated CdHA's of various calcium deficiency by adding controlled abundances of H_3PO_4 solution into a $CaCO_3$ suspension followed by calcinations of the precipitates in air, and sintering compacts of the calcined powders under appropriate conditions. A calibrating dependence of the phase composition in the ceramics versus the acid abundance has been plotted which enabled preparing BCP ceramics of a desired and reproducible composition.

A correlation was found between characteristics of bands in ν_4-PO_4^{3-} domain in IR-spectra and annealing temperature (at fixed dwell-time) of nanostructured BCP materials during CdHA → β-TCP transformation. The correlation can be used for evaluating the HA/β-TCP ratio in the ceramics when CdHA compacts were used for sintering.

The density and microhardness in the dense BCP ceramics neglectly depended on the composition. However, the compressive strength got higher as the relative β-TCP amount increased in dense BCP ceramics.

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