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Thermally induced crystallization and phase evolution in powders derived from amorphous calcium phosphate precipitates with a Ca/P ratio of 1:1

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ABSTRACT

Calcium phosphate powders of calcium pyrophosphate α^1-CPP (the metastable phase of the high-temperature polymorph α-CPP) and the polymorph β-CPP (stable in this range), of α^1-CPP, β-CPP, α^1-TCP (metastable polymorph of the high-temperature phase α-tricalcium phosphate) and β-tricalcium phosphate β-TCP were prepared by heating amorphous calcium phosphate (ACP) precipitates with the nominal Ca/P ratio of 1:1 by nitrate synthesis. α^1-CPP/β-CPP resulted from a crystallization at 530–640 °C and subsequent heating to 980 °C of unwashed and lyophilized ACP. α^1-CPP/β-CPP/α^1-TCP/β-TCP was formed by crystallization at 620–720 °C, followed by heating of six-time washed and lyophilized ACP precipitates from an ultra-short synthesis. The activation energy for the crystallization of ACP to α^1-CPP was determined with 165 kJ mol^{-1}. The reason for the occurrence of the TCP phases (Ca/P ratio = 1.5) from ACP (Ca/P ratio = 1) is discussed. The powders are prospective biomaterials for bone substitution because they combine effective bioactive phases with the metastable polymorphs α^1-CPP and α^1-TCP.

1. Introduction

Calcium phosphates based on hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (HA), and β-tricalcium phosphate, β-$Ca_3(PO_4)_2$ (β-TCP), are widely used as biomaterials, especially for bone substitution and bone repair [1,2]. Calcium phosphate biomaterials based on α-tricalcium phosphate, α-$Ca_3(PO_4)_2$ (α-TCP), have also been discussed because α-TCP is better soluble (i.e. biodegradable) than HA and β-TCP [3,4]. Special attention has been paid to biomaterials prepared from amorphous calcium phosphate (ACP) [5]. These are usually fine-grained and sometimes contain metastable phases. Therefore, the biomedical characteristics (biodegradation rate, bioactivity, and osteoconductivity) of these biomaterials can be superior to conventional sintered calcium phosphate ceramics [6–8].

Calcium pyrophosphate, $Ca_2P_2O_7$ (CPP), can be prepared by the thermal decomposition of dicalcium phosphate dihydrate, $CaHPO_4 \cdot 2\ H_2O$ (brushite, DCPD), or dicalcium phosphate anhydrate, $CaHPO_4$ (monetite, DCPA). Three polymorphs are known: γ-CPP is formed from DCPA at relatively low temperatures of 300–500 °C, β-CPP is formed from γ-CPP in the range of 600–800 °C, and β-CPP transforms into the high-temperature polymorph α-CPP above 1200 °C [9,10]. Few kinetic data were obtained and many are contradictory. For instance, the activation energy for the transformation of DCPA to γ-CPP was reported with 205 kJ mol^{-1} [11] and 135 kJ mol^{-1} [12].

Pyrophosphate ions $P_2O_7^{4-}$ are thought to participate in the bone mineralization process [13]. Also, it was revealed in one of the first reports on application of CPP as biomaterials that after only 10 weeks of implantation the sintered CPP had formed a bond with bone [14]. Subsequent studies have shown that CPP ceramics are more rapidly resorbed in vivo than sintered HA [15,16].

CPP ceramics have been prepared by different routes [15,18–20]. Typically, the CPP ceramics were prepared by a high-temperature solid-state reaction [15]. As a consequence, the ceramics consisted of highly crystalline micrograins; such perfect and coarse grains are known to reduce the solubility of ceramics [17]. Another CPP ceramics were fabricated using 3D powder printing and a two-step process [18]. Firstly, a printed structure of DCPD was formed using an industrial printing system, and then, the printed matrix was heat-treated at 1100–1300 °C. The TCP/α-CPP ceramics resulted from the high-temperature sintering were also coarse-grained. It was reported that a calcination at intermediate temperature of ACP with an atomic Ca/P ratio of 1:1 prepared by flame spray synthesis resulted in the high-temperature polymorph α-CPP [19]. The flame

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spray synthesis has been successfully used for production of carbon, silicate and titanium nanoparticles. However, the method associated with rather complex apparatus, explosive supporting gases (oxygen and methane) and therefore safety problems is hardly the best choice for preparation of CPP particles.

A simple operation process, available ware, few (or no) special equipment, low cost along with a sufficient yield are much more desirable. The sol–gel route, which meets the majority of these requirements, was recently employed to prepare a β-CPP powder [20]. Nanocrystalline powders of other CPP polymorphs and their mixtures (particularly including the metastable α-CPP polymorph) are thought to be also prospective for processing bioceramics.

Here we report on the preparation of ACP with a Ca/P ratio of 1:1 by an easy, convenient, inexpensive, and efficient wet nitrate synthesis. Furthermore, its crystallization and phase transitions with the aim to obtain improved CPP ceramics are presented.

2. Materials and methods

The preparation of ACP with a Ca/P ratio of 1:1 (as in DCPA) was based on a fast precipitation modification of the classical nitrate synthesis [21]. An aqueous solution of $(NH_4)_2HPO_4$ (0.43 M) was rapidly pumped into a vessel with an aqueous solution of $Ca(NO_3)_2$ (0.43 M), giving the molar Ca/P ratio of 1:1, and leading to the following chemical reaction:

$$Ca(NO_3)_2+(NH_4)_2HPO_4 \rightarrow CaHPO_4+2\ NH_4NO_3 \qquad (1)$$

Besides $CaHPO_4$, the reaction also leads to the water-soluble product ammonium nitrate. The reactants were analytical grade (Merck, Germany), and freshly distilled water was used as solvent. The pH of both solutions was adjusted before the mixing with aqueous ammonia to 10.5. The temperature was kept at 5 °C. The vessel with the mixture was tightly closed, vigorously shaken, and put into a freezer. Two durations were used for the synthesis. In the first case, the whole process from the start of mixing to placing the vessel into the deep-freezer was shorter than 1 min (denoted as ultra-short synthesis in the following). In the other case, the stirring was performed for 5 min (denoted as short synthesis in the following). The pH in the mother solution slightly dropped during the syntheses, the lowest value was 10.

The vessel was transferred into the freezer at −25 °C for 24 h (the mass in the vessel became frozen after about 10 min). The frozen mass was then taken from the freezer and slowly warmed up to 0 °C. The molten ice was continuously removed by blotting paper. All this time, the temperature in the ice-water-slurry system remained in the range of 1–3 °C. A part of the resultant slurry was returned to the freezer (unwashed slurry) washed six times with cold aqueous ammonia solution (5 °C, pH 10–11, the wash waters were decanted) and was also then returned to the freezer (six times-washed slurry). By this washing, the easily water-soluble ammonium nitrate was removed. The both slurries were kept in the freezer until their weights became stable. Dry powders were obtained that are denoted as UW (from unwashed slurry) and 6W (six times washed slurry) in the following. Before analysis, the powders were additionally dried in vacuum. Freeze-drying the slurries was a necessary procedure to get ACP because drying only in air and/or in vacuum resulted in nanocrystalline powders [22].

Powder samples were examined as prepared and after annealing in air in the range of 25–1000 °C. The samples were heated to the given temperature ($5\ K\ min^{-1}$), removed from the furnace, allowed to freely cool to room temperature, and analyzed. They were studied by X-ray powder diffraction (XRD) using Bruker D8 Advance and Philips APDW 40C instruments in Bragg–Brentano mode with Cu Kα radiation (1.54 Å, 40 kV and 40 mA). For the qualitative phase analysis with a Diffrac.Suite EVA V1.2 from Bruker the pattern of monoclinic α-$Ca_2P_2O_7$ (α-CPP, #01-073-0440) and tetragonal β-$Ca_2P_2O_7$ (β-CPP, #00-033-0297) as well of monoclinic α-$Ca_3(PO_4)_2$ (α-TCP, #01-070-0364) and trigonal β-$Ca_3(PO_4)_2$ (β-TCP, #00-009-0169) from the ICDD database were used as reference. Rietveld refinement with the program package TOPAS 4.2 from Bruker was performed to determine the weight amount of crystalline phases and to calculate the lattice parameters and crystallite sizes (using the Scherrer equation). For each Rietveld refinement, the instrumental correction as determined with a powder sample LaB_6 from NIST (National Institute of Standards and Technology) as standard reference material (SRM 660b; $a(LaB_6)=4.15689$ Å) was taken into account. The samples were also studied by thermogravimetry and differential thermal analysis, TG–DTA (Q-Derivatograph, Hungary, $5\ K\ min^{-1}$, air atmosphere), infrared spectrometry (IR; Perkin-Elmer 1720X and Specord 751, Germany; KBr-pellet technique). The morphology was observed by scanning electron microscopy operating in a high vacuum with gold/palladium-sputtered samples (ESEM Quanta 400 FEG instrument, FEI). Calcium amounts in the powder samples were determined by atomic absorption spectroscopy (Thermo Electron Corporations, M-series AA spectrometer). Corresponding amounts of orthophosphate were found by colorimetry using the molybdenum blue method (Varian Cary Win UV spectrophotometer, $\lambda=725$ nm). Each sample was given five measurements. The accuracy of the measurement was ~0.2% for calcium, ~0.02% for phosphorus, and ~0.2% for Ca/P. The Ca/P ratio in the heated (sintered) samples was determined by EDX spectroscopy (Genesis 4000, SUTW – Si detector) from five non overlapping fields selected randomly. EDX results believed to be accurate to within ~5%.

3. Results and discussion

Ceramics are normally prepared by sintering powder compacts at high temperatures. In order to find out whether ceramics with metastable calcium phosphate phases can be prepared, the thermal behavior of the UW and 6W powders was examined and compared. We assume that the washing procedure not only removes the by-product ammonium nitrate and possible residual reactants but also affects the Ca/P ratio of the powder [23,24].

3.1. UW powders

The XRD and SEM patterns showed that the initial powder was X-ray amorphous and consisted of nanoparticles (Fig. 1a and a′). Upon heating to 980 °C, nanocrystalline β-CPP was detected (Fig. 1b and b′). Notably, the Ca/P ratio of both the initial powder and the nanocrystalline β-CPP was 1:1 (Fig. 1a′ and b′) as in the mother solution. These results were in accordance with earlier data [19] and confirmed that the synthesis was correctly performed.

The TG curve of the UW sample showed a continuous mass loss of 25.2 wt% (Fig. 2a). The derivative of the mass loss (DTG) showed three ranges of the increased mass loss (Fig. 2a′) that we attribute to the release of adsorbed water at about 90 °C (peak 1) [25], the decomposition of residual $(NH_4)_2HPO_4$ in the range of 110–270 °C along with the decomposition of NH_4NO_3 at 270 °C (peak 2) [21] and of residual $Ca(NO_3)_2$ at 585 °C (peak 3) [26]. There was no mass loss observed above 650 °C. The DTA curve (Fig. 3a) showed a broad complex endothermal peak in the range of 50–300 °C due to the desorption of water along with the decomposition of residual $(NH_4)_2HPO_4$ and NH_4NO_3 [26]. The second well-pronounced endothermal peak in the range of 300–510 °C was associated with the condensation reaction of monetite [11,12]

$$2CaHPO_4 \rightarrow Ca_2P_2O_7+H_2O\uparrow.$$