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Mechanochemical-hydrothermal synthesis of calcium phosphate powders with coupled magnesium and carbonate substitution

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Abstract

Magnesium- and carbonate-substituted calcium phosphate powders (Mg-, CO_3-CaP) with various crystallinity levels were prepared at room temperature via a heterogeneous reaction between $MgCO_3/Ca(OH)_2$ powders and an $(NH_4)_2HPO_4$ solution using the mechanochemical-hydrothermal route. X-ray diffraction, infrared spectroscopy, and thermogravimetric analysis were performed. It was determined that the powders containing both Mg^{2+} and CO_3^{2-} ions were incorporated uniformly into an amorphous calcium phosphate phase while in contrast, the as-prepared powder free of these dopants was crystalline phase-pure, stoichiometric hydroxyapatite. Dynamic light scattering revealed that the average particle size of the room temperature Mg-, CO_3-CaP powders was in the range of 482 nm-700 nm with a specific surface area between 53 and 91 m^2/g. Scanning electron microscopy confirmed that the Mg-, CO_3-CaP powders consisted of agglomerates of equiaxed, ≈20–35 nm crystals.

Keywords: Calcium phosphate; Hydroxyapatite; Magnesium; Nanoparticle; Hydrothermal Synthesis; Mechanochemical synthesis

1. Introduction

Hydroxyapatite [HAp, chemical formula $Ca_{10}(PO_4)_6(OH)_2$] has attracted attention of researchers during the past 30 years as an implant material because of its excellent biocompatibility and bioactivity [1,2]. It has also been extensively investigated for non-medical applications such as packing media for column chromatography, gas sensors, catalysts, host material for lasers, and plant growth substrates. All properties of HAp, including bioactivity, biocompatibility, solubility, and adsorption properties can be tailored over a wide range by modifying the composition through ionic substitutions [1–4].

Mg^{2+} and CO_3^{2-} are two of the main ionic substitutions in biological apatites [4]. Enamel, dentin and bone contain respectively 0.44 wt%, 1.23 wt%, and 0.72 wt% of Mg^{2+} and 3.5 wt%, 5.6 wt%, and 7.4 wt% of CO_3^{2-} [4]. Therefore the Mg^{2+}- and/or CO_3^{2-}-substituted HAp materials are expected to have excellent biocompatibility and properties, which can be favorably compared with those of hard tissue. Bonfield and Gibson suggested coupled Mg^{2+} (up to 0.5 wt%) and CO_3^{2-} (up to 1 wt%) substitution in HAp synthesized by precipitation from aqueous solutions as a raw material for bone implants fabrication [5]. Dolci et al. mentioned the use of 0.5–200 nm HAp powder containing up to 25.4 wt% of Mg^{2+} for odontostomatologic applications [6]. It has been postulated that magnesium directly stimulates osteoblast proliferation with an effect comparable to that of insulin (a known growth factor for osteoblast) [7]. Sintered carbonated HAp ceramics exhibit in vitro cell resorption rate similar to the resorption rate of the natural bone minerals [8], which is higher than that of

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pure HAp ceramics [8,9]. Recent in vivo study using rats indicated that the dissolution rate of dense sintered carbonated HAp ceramics implanted subcutaneously was intermediate between β-tricalcium phosphate (β-TCP) and pure HAp [10]. In another in vivo study, it was found that the quantity of intermedullar bone formed around carbonated HAp implants increased with carbonate concentration [11]. Carbonated HAp bone cements passed preliminary tests for injectable, in situ-hardened bone fillers [12] and screw fixations [13]. A self-setting bone paste (Norian SRS) that forms a carbonated apatite upon complete reaction was recently approved to stabilize certain metaphyseal distal radius fractures and fill osseous defects. Nanosized CO_3^{2-}-substituted HAp crystals were used to fabricate HAp/collagen biodegradable composites [14].

The above studies indicate that Mg^{2+}- and/or CO_3^{2-}-substituted HAp ceramics may be superior to pure HAp for implant applications. Therefore, development of new synthesis techniques for substituted HAp powders with controlled morphology and chemical composition is of great importance. Low crystallinity and nanometer size characteristics for Mg^{2+}- and/or CO_3^{2-}-substituted HAp powders render them similar to natural bone [2,14]. In addition, controlling level of Mg^{2+} and CO_3^{2-} substitution in HAp is a convenient way to change crystallinity, solubility and morphology of the synthesized crystals [3,4,15], which subsequently impact properties of the HAp-based biomaterials [1,2].

In our earlier studies we have demonstrated that HAp powders with stoichiometric composition and also substituted with either Mg^{2+} or CO_3^{2-} could be prepared at room temperature from heterogeneous reactions between $Ca(OH)_2$/$CaCO_3$/Na_2CO_3/$Mg(OH)_2$ powders and an $(NH_4)_2HPO_4$ solution via the mechanochemical-hydrothermal route [16–18]. In the present paper, we will introduce a mechanochemical-hydrothermal method for room-temperature preparation of apatitic calcium phosphate powders with coupled magnesium and carbonate substitution.

2. Experimental procedure

2.1. Mechanochemical-hydrothermal synthesis

The attempted chemical compositions corresponded to the x values of 0.0, 1.0, and 2.0 in the following simplified chemical formula of apatitic Mg^{2+}- and CO_3^{2-}-substituted calcium phosphate (denoted hereafter as Mg-, CO_3-CaP), $Ca_{10-x}Mg_x(PO_4)_{6-x}(CO_3)_x(OH)_2$. This chemical formula does not take into account either increasing HPO_4^{2-} substitution or formation of related lattice defects with increasing Mg^{2+} and CO_3^{2-} content; therefore, it can be used as an approximate notation. $Ca(OH)_2$, $MgCO_3$, and solid $(NH_4)_2HPO_4$ (all analytical grade, Alfa Aesar, Ward Hill, MA) were used as reactants for synthesis of Mg-, CO_3-CaP. Their purity was confirmed by X-ray diffraction and thermogravimetry. First, suspensions containing powder mixtures of 19.153–25.251 g $Ca(OH)_2$ and 0–5.405 g $MgCO_3$ in 350 mL of deionized water were prepared inside a 500 mL glass beaker. Subsequently, 25.400–26.736 g of $(NH_4)_2HPO_4$ powder was slowly added to the same beaker with constant vigorous magnetic stirring for about 10 min. The (Ca + Mg)/P molar ratio in the starting slurries was 1.67. The concentration of water and other volatile species in the reactants was measured by thermal gravimetric analysis (TGA) to ensure stoichiometric control. Slurry pH was measured using a glass electrode connected to a pH-meter (Accumet® Model 805 MP, Fisher Scientific, Pittsburgh, PA) and calibrated with respect to a buffer solution (pH = 10.00, Fisher Scientific, Pittsburgh, PA). The pH of all slurries was 10.2–10.5. The mechanochemical-hydrothermal synthesis was performed by placing the slurry into a laboratory-scale multi-ring media mill (model MIC-0, NARA Machinery Co., Tokyo, Japan) equipped with a zirconia liner and zirconia ring grinding media. The comminuting mechanism of this mill has been described in detail elsewhere [16–19].

Mechanochemical-hydrothermal reaction of the slurry was carried out in air, initially at a rotation speed of 1500 rpm for 1 h and then at 800 rpm for 4 h. Temperature during the reaction was measured using a thermocouple, which ranged between 12°C and 17°C at 1500 rpm and 8°C and 12°C at 800 rpm. Washing of the solid phase after the mechanochemical-hydrothermal synthesis was accomplished by 2–6 cycles of shaking the solid with distilled water in 2–6 HDPE 250 mL bottles using a hand shaker machine (Model M37615, Barnstead/Thermolyne, Dubuque, Iowa) followed by centrifuging at 4500 rpm for 30 min (Induction Drive Centrifuge, Model J2-21 M, Beckman Instruments, Fullerton, CA). The washed solid phase was dried in an oven at 70°C for 24 h (Isotemp® oven, model 230G, Fisher Scientific, Pittsburgh, PA) and ground into powder using an Agate mortar and pestle. These powders were referred to as "as-prepared Mg-, CO_3-CaP" in the entire paper. A typical batch size of as-prepared Mg-, CO_3-CaP powder was about 30 g.

2.2. Materials characterization

In order to check thermal stability of the synthesized Mg-, CO_3-CaP phases herein referred to "heat-treated", a small quantity of each as-prepared powder was placed in an alumina crucible and was subsequently heat treated in air at various temperatures for 1 h with a heating rate of 10°C/min. (Rapid Temperature Furnace, CM Inc., Bloomfield, NJ). Samples with $x = 1.0$ and 2.0 were heat-treated at 500°C and 700°C, while a sample with $x = 0.0$ (stoichiometric HAp composition) was heat-treated only at 900°C. The samples were cooled together with the furnace (average cooling rate ≈6°C/min) and removed from the furnace when it cooled down to the room temperature.

X-ray diffraction characterization of all batches of as-prepared and heat-treated Mg-, CO_3-CaP powders was performed using Ni filtered Cu $K\alpha$ radiation. Samples were analyzed over 2θ range of 10–70° at a scan rate of 2.4°/min, with a sampling interval of 0.05° (XRD, Kristalloflex D-500, Siemens Analytical X-ray Instrument Inc., Madison, WI). Crystallographic identification of the synthesized phases was accomplished by comparing the experimental XRD patterns to standards compiled by the Joint Committee on Powder Diffraction and Standards (JCPDS), which corresponded to card ♯09–0432 for HAp, ♯08–0479 for $MgCO_3$, and ♯09–0169 for whitlockite.

Specific surface area of all batches of as-prepared Mg-, CO_3-CaP powders was measured using the BET method utilizing adsorption of N_2 gas (purity 99.99%, Matheson Co., Bridgeport, NJ) at –196°C (Micromeritics 2375, Micromeritics, Norcross, GA). For this purpose, 0.10–0.30 g of the Mg-, CO_3-CaP powder was outgased for 2–4 h at 120°C. Particle size of the primary crystals was estimated from the nitrogen adsorption isotherms using the BET method to calculate equivalent spherical diameter, or BET particle diameter (d_{BET}), from the following fundamental equation: $d_{\mathrm{BET}} = 6/(\rho \cdot S_{\mathrm{w}})$, where ρ is density and S_{w} is the specific surface area [20]. A density of 3.156 g/cm^3, which is a theoretical density of stoichiometric HAp [3], was assumed in the d_{BET} calculations (this assumption could lead to some error in the case of the synthesized ACP powders, since their theoretical density is unknown).

Particle size distributions of all batches of as-prepared Mg-, CO_3-CaP powders were determined by dynamic light scattering at a wavelength of 632.8 nm (DLS, model DLS-700, Otsuka Electronics Co., Osaka, Japan). Samples for the DLS measurements were prepared by dispersing small amounts of powder in ethanol (filtered using a 0.2 μm filter) followed by treatment in an ultrasonic bath for 10 min. After transferring to the sample holder, the suspensions were diluted again using filtered ethanol and ultrasonicated for 3 min. The measurement conditions used included a sampling time of 80 μs and 100 accumulations. A viscosity of 1.19 cP and refractive index of 1.36 were used for calculations.

Size and degree of agglomeration of the synthesized particles in selected batches of as-prepared Mg-, CO_3-CaP were studied using field emission scanning electron microscope at 1.0–2.0 kV with a working distance of 2–5 mm (FESEM, Model DSM 962, Gemini, Carl Zeiss, Inc., Thornwood, NY). In order to prepare a sample for the FESEM analysis, a small quantity of powder was suspended in ethanol, placed in an ultrasonic bath for 10 min. and transferred on graphite tape mounted on sample holders. No conductive coating was used.

Infrared spectra of the as-prepared Mg-, CO_3-CaP powders were obtained in the range of 400–4000 cm^{-1} using an infrared Fourier-transform spectrometer (FTIR, model 1720-X, Perkin Elmer Co., Norwalk, CT). For this purpose each powder was mixed with KBr in the proportion 1/150 (by weight) for 15 min. and pressed into a pellet using a hand press. The FTIR spectra were acquired with resolution of 2.0 cm^{-1}.

Thermogravimetric analysis (TGA, model TGA-6, Perkin Elmer Co., Norwalk, CT) was performed on all batches of as-prepared Mg-, CO_3-CaP powders up to a maximum temperature of 950°C with 0.1–0.3°C sampling intervals, using a heating rate of 5°C/min in a flowing air atmosphere (20 mL/min).

3. Results and discussion

3.1. Mg-, CO_3-CaP synthesis

XRD patterns of the as prepared Mg-, CO_3-CaP powders are shown in Fig. 1. The XRD pattern of the sample with $x = 0.0$ (i.e., undoped HAp) shows only phase-pure HAp phase without any foreign peaks (Fig. 1a). The XRD patterns of the powders (Figs. 1b and c) with $x = 1.0-2.0$ (i.e., doped with Mg^{2+} and CO_3^{2-}) revealed broad peaks around $2\Theta = 28-32°$ and $2\Theta = 45-55°$, which are typical for amorphous calcium

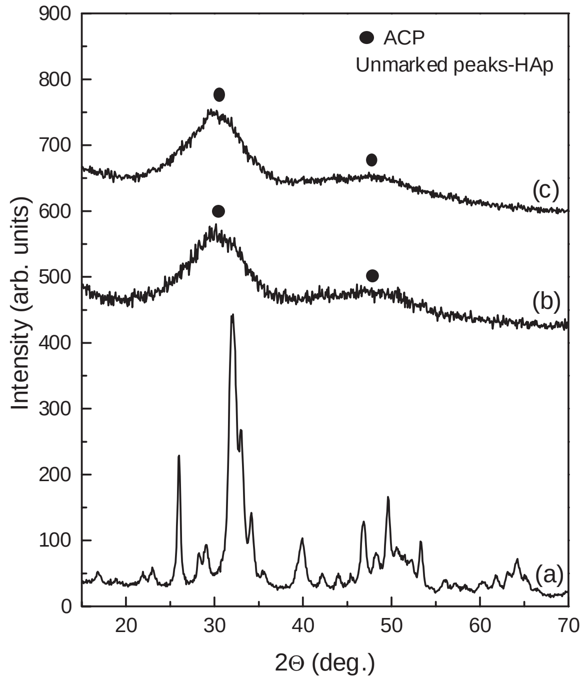

Fig. 1. XRD patterns of as-prepared Mg-, CO_3-CaP powders: (a) $x = 0.0$ (undoped HAp); (b) $x = 1.0$; and (c) $x = 2.0$.

phosphate (ACP) [3]. In view of limited solubility of the reactants in water (solubilities of $Ca(OH)_2$ and $MgCO_3$ in water are respectively 1.85 g/L and 0.106 g/L), the absence of any unreacted $Ca(OH)_2$ and/or $MgCO_3$ in the synthesized Mg-, CO_3-CaP strongly suggests that almost all calcium, magnesium, and carbonate from the reactants were incorporated into the precipitated calcium phosphate phases.

Fig. 2 shows XRD patterns of the heat-treated Mg-, CO_3-CaP powders that confirm total incorporation of the reacting ions in the as-prepared Mg-, CO_3-CaP samples. The Mg-, CO_3-CaP samples with $x = 1.0-2.0$ remained amorphous after heat treatment at 500°C for 1 h, as shown in Fig. 2b. However, very well developed XRD peaks derived from both whitlockite and HAp were detected in these samples after heat treatment at 700°C for 1 h (Fig. 2c), indicating presence of both Mg^{2+} and CO_3^{2-} in the ACP phase [4]. In contrast, the undoped HAp powder ($x = 0.0$) did not decompose after heat treatment at 900°C for 1 h (Fig. 2a), which serves as evidence of its stoichiometric composition [3,4]. The only change observed in the undoped heat-treated HAp powder was narrowing of the XRD peaks, which could be ascribed to the increased crystal size of HAp at elevated temperatures.

In our experiments, in the absence of Mg^{2+} and CO_3^{2-}, highly crystalline and stoichiometric HAp was obtained, while in the presence of these ions, only ACP could be synthesized under otherwise equal conditions. Observed increasing lattice disorder in the powders with $x = 1.0-2.0$ was very likely associated with increasing Mg^{2+} and CO_3^{2-} substitution, which has been widely reported in the literature, as reviewed in Refs. [3,4]. Presence of both Mg^{2+} and CO_3^{2-} ions increases stability of the ACP phase against conversion to apatite in an aqueous medium [4]. Upon heating above 600°C, Mg^{2+}- and CO_3^{2-}-substituted ACP can be converted into HAp and whitlockite, depending upon the initial chemical composition [4], which has been observed in the heat-treated samples with $x = 1.0-2.0$. The shift of the whitlockite peaks towards higher 2Θ values with respect to the Mg-free β-TCP (JCPDS card ♯09–0169) serves as evidence of Mg substitution in whitlockite. It is known that large amounts of Mg can substitute into the whitlockite and stabilize its lattice [4]. The HAp phase observed in the heat treated Mg-, CO_3-CaP powders probably contained some Mg^{2+} and CO_3^{2-} ions in the lattice as well.

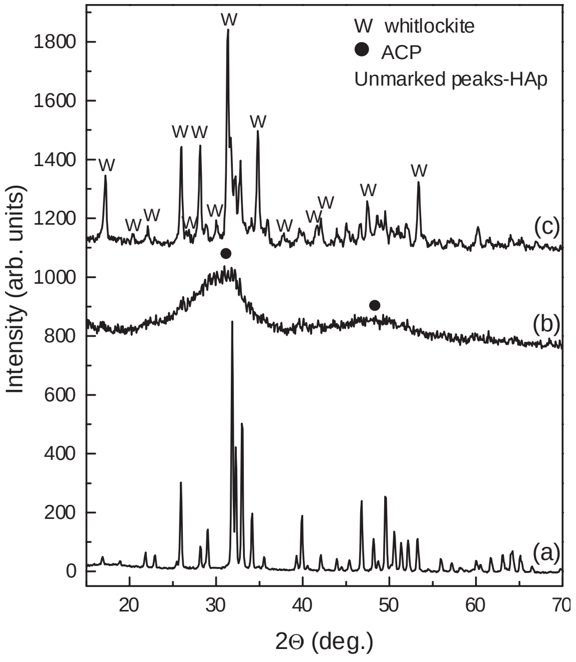

Fig. 2. XRD patterns of selected heat-treated Mg-, CO_3-CaP powders: (a) $x = 0.0$ (undoped HAp) heat treated at 900°C (1 h) in air; (b) $x = 1.0$ heat treated at 500°C (1 h) in air; and (c) $x = 1.0$ heat treated at 700°C (1 h) in air. XRD patterns of Mg-, CO_3-CaP powders with $x = 2.0$ heat-treated in air at 500°C (1 h) and 700°C (1 h) looked very similar to the heat-treated samples with $x = 1.0$.

FTIR spectra of the as prepared Mg-, CO_3-CaP powders are shown in Fig. 3. These are typical spectra of HAp (Fig. 3a) and carbonated ACP (Figs. 3b and c) showing PO_4^{3-}-derived bands at 478, 566, 605, 963, and 1030–1090 cm^{-1} and adsorbed water bands at 1630 cm^{-1} and 3000–3700 cm^{-1} [3,4]. High intensity of the CO_3^{2-}-derived bands between 1420 and 1480 cm^{-1} indicates presence of large quantities of carbonate in the synthesized Mg-, CO_3-CaP powders ($x = 1.0-2.0$). Presence of small amounts of CO_3^{2-} ions in the stoichiometric HAp powder was probably due to

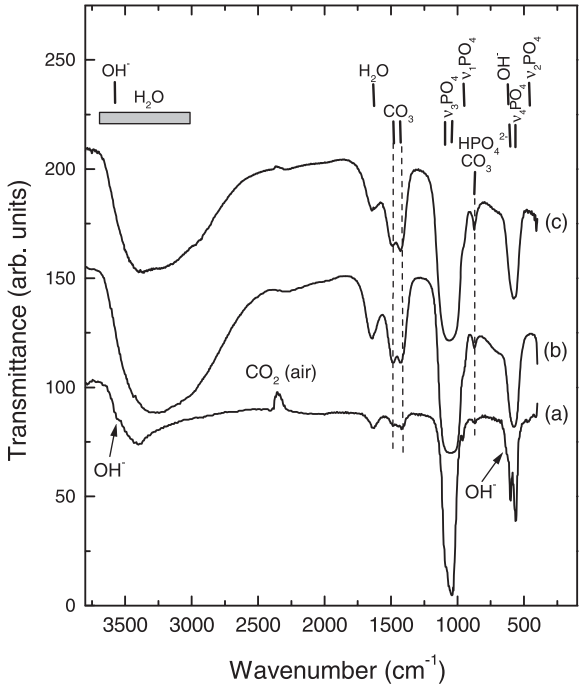

Fig. 3. FTIR spectra of the as-prepared Mg-, CO_3-CaP powders: (a) $x = 0.0$ (undoped HAp); (b) $x = 1.0$; and (c) $x = 2.0$.

conducting the experiments in air. The low intensity of both OH^--derived bands at 630 and 3570 cm^{-1}, which are visible only in the nominally stoichiometric HAp powder ($x = 0.0$), as well as loss of resolution of the PO_4^{3-}-derived bands with increasing x, was observed. These effects are typical for Mg-, CO_3-CaP synthesized by wet methods, which can be explained by increasing lattice disorder due to Mg^{2+} and CO_3^{2-} substitution in HAp [4]. Very low intensity of the OH^--derived bands could be also caused by the presence of adsorbed water combined with relatively high surface area of the Mg-, CO_3-CaP powders. From the obtained FTIR spectra, it is difficult to distinguish the presence of HPO_4^{2-} groups since a HPO_4^{2-}-derived band overlaps with a CO_3^{2-}-derived band around 870 cm^{-1} [4].

TGA analysis of the as prepared Mg-, CO_3-CaP powders in the temperature range of 25–950°C (Fig. 4), confirmed results of the XRD and the FTIR analyses. No weight changes associated with decomposition of $Ca(OH)_2$ (400°C) and/or $MgCO_3$ (350°C) were observed in any of the TGA curves recorded for the as prepared Mg-, CO_3-CaP, further supporting complete reaction to phase pure product. In all the as-prepared Mg-, CO_3-CaP powders, significant loss of weight observed up to approximately 400–500°C could be ascribed to the loss of adsorbed water (up to $\approx$200°C) followed by the lattice water [3]. In the samples with Mg^{2+} and CO_3^{2-} substitution ($x = 1.0-2.0$), the loss of CO_2 could contribute to the total weight loss starting from 350°C (or even lower) as reported in Ref. [3]. Slightly below 700°C, HAp and whitlockite crystallized from the ACP. The crystallization manifested itself as a sudden decrease of slope of the TGA curves. The Mg-, CO_3-CaP samples with $x = 1.0$ (Fig. 4b) and $x = 2.0$ (Fig. 4c) exhibited gradual weight loss at temperatures higher than 400–500°C, which could be explained by further loss of the lattice water and CO_2. Conversely, the undoped HAp powder ($x = 0.0$) exhibited minimal weight loss (Fig. 4a) above 450°C, which is typical for near stoichiometric HAp. The minimal weight loss is most likely the result of the loss of trace quantities of lattice water and CO_2.

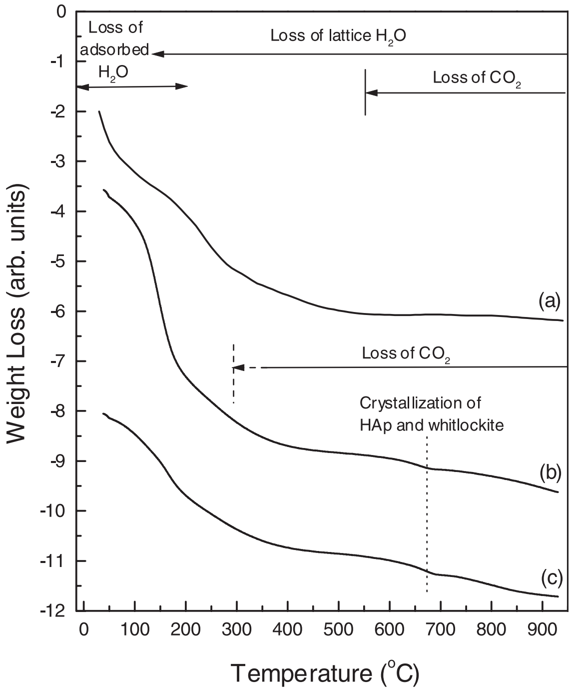

Fig. 4. TGA curves of the as-prepared Mg-, CO_3-CaP powders: (a) $x = 0.0$ (undoped HAp); (b) $x = 1.0$; and (c) $x = 2.0$.

Specific surface area of the as prepared Mg-, CO_3-CaP powders ranged between 91 m^2/g for $x = 0.0$ and 53 m^2/g for $x = 1.0$, which corresponds to an estimated equivalent spherical diameter (d_{BET}) of 21–36 nm (Table 1). Specific surface area of the samples with Mg^{2+} and CO_3^{2-} substitution ($x = 1.0-2.0$) was lower than that of undoped HAp ($x = 0.0$), as shown in Table 1. The particle size distributions were in all cases single-modal with median values ranging between 359 and 709 nm. Corresponding average particle sizes were in the range of 482–700 nm (Table 1). These measurements very strongly indicate presence of aggregates and/or agglomerates consisting of nanosized primary particles with a size less than 36 nm. Results of FESEM observations, shown in Fig. 5, were in a good agreement with the results of both BET and DLS measurements. The as-prepared Mg-, CO_3-CaP powders contained large agglomerates, which consisted of nanosized particles with equiaxed morphology (Fig. 5). The particles of as-prepared Mg-, CO_3-CaP (Figs. 5b and c) were clearly larger than the crystals of undoped HAp (Fig. 5a).

3.2. Characteristics of the mechanochemical-hydrothermal synthesis

The Mg-, CO_3-CaP powders synthesized in the present work by the mechanochemical-hydrothermal method at room temperature share several common features. All of them consist of nanosized crystals that are agglomerated and/or aggregated. The concentration of the substituting Mg^{2+} and CO_3^{2-} ions can be controlled by changing concentration of the corresponding reactants. The absence of any unreacted species in the as-prepared Mg-, CO_3-CaP powders, as well as the

Table 1
Characteristics of the as-prepared Mg-, CO_3-CaP powders

x in the Mg-, CO_3-CaP formula	Specific surface area (m^2/g)	Equivalent spherical diameter, d_{BET} (nm)	Average particle size (nm)	Median particle size (nm)
0.0	91	21.0	685	663
1.0	53	35.9	482	359
2.0	68	28.0	700	709

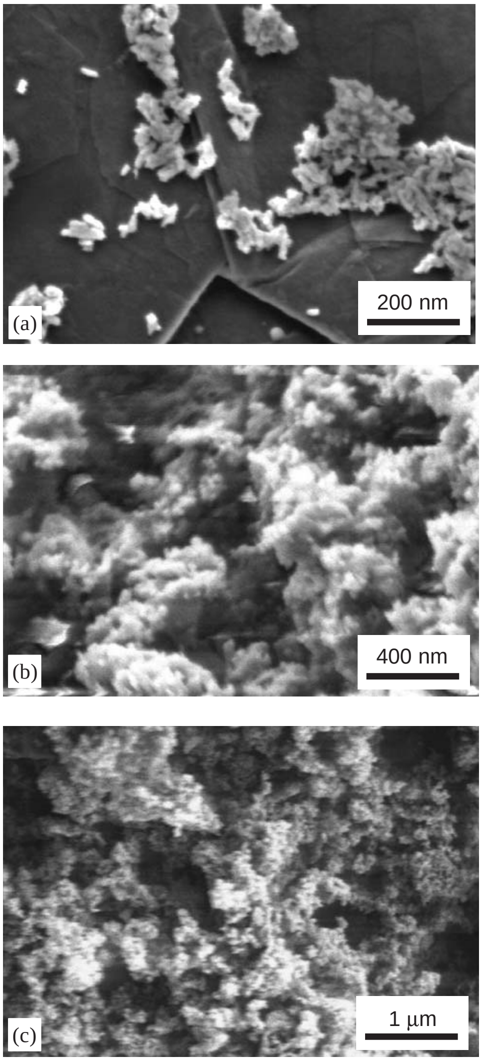

Fig. 5. FESEM photographs of the as-prepared Mg-, CO_3-CaP powders showing agglomeration of nanosized particles. (a) $x = 0.0$ (undoped HAp); (b) $x = 1.0$; (c) $x = 2.0$.

XRD patterns of the heat-treated samples, indicate high effectiveness of the room temperature mechanochemical-hydrothermal synthesis to produce pure and homogeneous Mg-, CO_3-CaP powders. In the absence of Mg^{2+} and CO_3^{2-} ions, the mechanochemical-hydrothermal technique produced stoichiometric and highly crystalline HAp powder. However, in the presence of large quantities of the substituting ions, which both destabilize the HAp lattice [3,4] only ACP could be synthesized. This effect seems to be related to the crystal chemistry of HAp, rather than to the mechanochemical-hydrothermal synthesis technique, which usually yields highly crystalline HAp powders [16–18]. Independent control of the crystal size, morphology, and agglomerate size distribution will require further research. Many of these phenomena were already observed in our earlier work on carbonated and Mg-doped HAp powders [17,18] and seem to be typical for the mechanochemical-hydrothermal synthesis of calcium phosphate powders.

The described synthesis reactions occur in an alkaline environment, which is very important because high pH values favor formation of the apatitic phases [3,4]. The mechanochemical-hydrothermal synthesis of Mg-HAp using $Ca(OH)_2/MgCO_3$ and $(NH_4)_2HPO_4$ occurs with participation of the liquid phase because one of the reactants, namely $(NH_4)_2HPO_4$ dissolves easily in water. Solubility of $MgCO_3$, $Ca(OH)_2$, and $(NH_4)_2HPO_4$ in water at room temperature is 0.106, 1.85, and 575 g/L, respectively [21]. Our results emphasize the importance of an aqueous solution, which actively participates in the synthesis reaction by dissolving one of the reactants, i.e., $(NH_4)_2HPO_4$.

Previous research on mechanochemical and mechanochemical-hydrothermal synthesis of HAp accomplished in other groups did not take advantage of water as a solvent, as reviewed in Refs. [16–18]. The aqueous solution can actively participate in the mechanochemical reaction by acceleration of dissolution, diffusion, adsorption, reaction rate, and crystallization [22,23]. In the mechanochemical-hydrothermal process, water actively participated in the synthesis by both dissolving one of the reacting powders as well as serves as a reactant to produce highly crystalline product with precisely controlled chemical composition, which is not observed with the conventional mechanochemical synthesis. The classical mechanochemical synthesis involves only solid-state reaction; therefore, it should be clearly distinguished from the mechanochemical-hydrothermal synthesis (aka, “wet” mechanochemical), which incorporates an aqueous phase in the system. The mechanochemical activation of slurries can generate local zones of high temperatures (up to 450–700°C) and high pressures due to friction effects and adiabatic heating of gas bubbles (if present in the slurry), while the overall temperature is close to the room temperature [24]. Thus, the mechanochemical-hydrothermal technique is located at the intersection of hydrothermal [22] and mechanochemical [23] processing. The mechanochemical-hydrothermal route produces comparable amounts of HAp powder as the hydrothermal processing but it requires lower temperature, i.e., room temperature, as compared to 90–200°C for the hydrothermal processing [25]. Thus, for the mechanochemical-hydrothermal processing, there is no need for a pressure vessel and external heating, which makes it very convenient for process scale-up.

4. Summary

Room-temperature mechanochemical-hydrothermal synthesis of magnesium- and carbonate-substituted calcium phosphate powders (Mg-, CO_3-CaP) has been accomplished via a heterogeneous reaction between $MgCO_3/Ca(OH)_2$ powders and an $(NH_4)_2HPO_4$ aqueous solution. The HAp powders without Mg^{2+} and CO_3^{2-} ions exhibited high crystallinity and stoichiometry, while the compositions doped with various levels of both Mg^{2+} and CO_3^{2-} ions could be synthesized as amorphous calcium phosphate (ACP) only. Detailed characterization of both as-prepared and heat-treated Mg-, CO_3-CaP powders by XRD, FTIR, and TGA indicates complete incorporation of the reacting ions into the synthesized HAp or ACP phases. All synthesized powders formed aggregates of 20–35 nm equiaxed primary particles with specific surface area ranging between 53 and 91 m^2/g.

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References

[1] H. Aoki, Science and Medical Applications of Hydroxyapatite, Japanese Association of Apatite Science, Tokyo, 1991.
[2] W. Suchanek, M. Yoshimura, J. Mater. Res. 13 (1998) 94–117.
[3] J.C. Elliott, Structure and Chemistry of the Apatites and Other Calcium Orthophosphates, Elsevier, Amsterdam, 1994.
[4] R.Z. LeGeros, Calcium Phosphates in Oral Biology and Medicine, Karger AG, Basel, 1991.
[5] W. Bonfield, I.R. Gibson, Patent Application No. WO 99/32400, 1999.
[6] G. Dolci, R. Mongiorgi, C. Prati, G. Valdre, Patent Application No. WO 00/03747, 1998.
[7] C.C. Liu, J.K. Yeh, J.F. Aloia, J. Bone Miner. Res. 3 (1988) S104–S104.
[8] Y. Doi, T. Shibutani, Y. Moriwaki, T. Kajimoto, Y. Iwayama, J. Biomed. Mater. Res. 39 (1998) 603–610.
[9] Y. Doi, H. Iwanaga, T. Shibutani, Y. Moriwaki, Y. Iwayama, J. Biomed. Mater. Res. 47 (1999) 424–433.
[10] J. Barralet, M. Akao, H. Aoki, H. Aoki, J. Biomed. Mater. Res. (2000) 176–82.
[11] L.G. Ellies, J.M. Carter, J.R. Natiella, J.D.B. Featherstone, J. Biomed. Mater. Res. 22 (1988) 137–148.
[12] T.A. Schildhauer, A.P. Bennett, T.M. Wright, J.M. Lane, P.F. O'Leary, J. Orthop. Res. 17 (1999) 67–72.
[13] J.C. Lotz, S.S. Hu, D.F. Chiu, M. Yu, O. Colliou, R.D. Poser, Spine 22 (1997) 2716–2723.
[14] C. Du, F.Z. Cui, Q.L. Feng, X.D. Zhu, K. de Groot, J. Biomed. Mater. Res. 42 (1998) 540–558.
[15] N. Kanzaki, K. Onuma, G. Treboux, S. Tsutsumi, A. Ito, J. Phys. Chem. B 104 (2000) 4189–4194.
[16] P. Shuk, W.L. Suchanek, T. Hao, E. Gulliver, R.E. Riman, M. Senna, K.S. TenHuisen, V.F. Janas, J. Mater. Res. 16 (2001) 1231–1234.
[17] W.L. Suchanek, P. Shuk, K. Byrappa, R.E. Riman, K.S. TenHuisen, V.F. Janas, Biomaterials 23 (2002) 699–710.
[18] W.L. Suchanek, K. Byrappa, P. Shuk, R.E. Riman, K.S. TenHuisen, V.F. Janas, Biomaterials, (2003) in press.
[19] K. Hamada, M. Senna, J. Mater. Sci. 31 (1996) 1725–1728.
[20] T.A. Ring, Fundamentals of Ceramic Powder Processing and Synthesis, Academic Press, San Diego, 1996.
[21] CRC Handbook of Chemistry and Physics. 68th Edition (1987–1988), CRC Press, Boca Raton, 1987.
[22] R.E. Riman, W.L. Suchanek, M.M. Lencka, Ann. Chim. Sci. Mater. 27 (2002) 15–36.
[23] E. Avvakumov, M. Senna, N. Kosova, Soft Mechanochemical Synthesis: A Basis for New Chemical Technologies, Kluwer Academic Publishers, Boston, 2001.
[24] N.V. Kosova, A.Kh. Khabibullin, V.V. Boldyrev, Solid State Ionics 101–103 (1997) 53–58.
[25] R.E. Riman, W.L. Suchanek, K. Byrappa, C.S. Oakes, C.-W. Chen, P. Shuk, Solid State Ionics 151 (2002) 393–402.