Consiglio Nazionale
delle Ricerche

1ST BIENNIAL CONFERENCE

BioMaH

a cura di
Julietta V. Rau e Antonio Ravaglioli

MACROPOROUS RESORBABLE CERAMICS BASED ON HEAT-TREATED CALCIUM PHOSPHATES WITH LAYERED STRUCTURE

A. Tikhonov[a,*], P. Evdokimov[a,b], V. Putlayev[a,b], E. Kukueva[a], T. Safronova[b]
[a] *Department of Materials Science, Lomonosov Moscow State University, Russia*
[b] *Department of Chemistry, Lomonosov Moscow State University, Russia*
**e-mail: andytikhon94@gmail.com*

Keywords: biphasic ceramics, octacalcium phosphate, macroporous biomaterials, slip-casting

INTRODUCTION

Regenerative approach to the treatment of bone tissue is an actual way in modern medicine. Composite bioceramics made of calcium phosphates are the most prospective as bioactive implants for bone grafting. For a long time, synthetic hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (HAp), was extensively used in medicine for restoring bone damages because of its chemical and physical similarity to the inorganic constituent of bone tissue. The main disadvantage of such a material is low resorption (dissolution) rate and weak osteoconductivity. Nowadays, alternative materials are searched for a bone tissue replacement, e.g. biphasic composites derived from calcium pyrophosphate $Ca_2P_2O_7$ (CPP) and tricalcium phosphate $Ca_3(PO_4)_2$ (TCP) or TCP/HAp.

Convenient precursors to fabricate such mixtures are layered calcium phosphates, in particular, octacalcium phosphate $Ca_8(HPO_4)_2(PO_4)_4{\cdot}5H_2O$ (OCP) and $Ca_8(HPO_4)_{2-x}R_x(PO_4)_4{\cdot}5H_2O$ (intercalated-OCP), in which a hydrophosphate-anion is substituted by a carboxylic acid-anion (R). OCP became the thrust of the study due to its layered structure constructed of alternating apatitic and hydrated layers. Hydrophosphate groups in OCP hydrated layer can be replaced by carboxylate-anions, e.g. succinic- and citric-anions. Such a replacement leads to increasing of Ca/P ratio in substituted phosphate, and makes it possible to obtain biphasic ceramics with variable composition and bioresorption rate. Due to featured layered structure of OCP, OCP-crystals have a plate-like habitus. If dehydration of the OCP crystals proceeds topotactically while heat treating of the ceramic precursor, one can arrange conserved plate-like particles of the treated OCP-precursors rather tightly, like bricks, in the course of ceramic forming. This might have a beneficial effect on the strength of the ceramics. Additionally, in sense of improvement of osteoconductive properties, macroporous ceramics with tailored pore architecture are to be created.

This work, thus, was aimed at elaboration of the powder precursors derived from heat treated OCP, in order to fabricate biphasic macroporous ceramics (TCP/CPP, TCP/HAp) with variable Ca/P ratio and phase composition. This scope of the work assumes a search for synthesis conditions of OCP (both “pure” and “intercalated” ones), as well as further study of their thermolysis and the ways to fabricate macroporous osteoconductive ceramics.

RESULTS AND DISCUSSION

Brief description of T-pH conditions of OCP synthesis was done with pH-titration and pH-stating. Properties of as-synthesized samples, as well as thermolysed ones, were characterized by powder X-ray diffraction (powder XRD), simultaneous thermal analysis (STA), infrared spectroscopy (IR) and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDX). Linear shrinkage of dense ceramics during its sintering was studied by dilatometry and by geometrical measurements.

In this study, substitution of HPO_4-anions was done by treatment of ☒-TCP aqueous suspension in buffer solutions of succinic acid (H_2Suc, Suc = $OOC(CH_2)_2COO^{2-}$) and citric acid (H_3Cit, Cit = $C_3H_5O(COO)_3^{3-}$) at definite temperatures and pH-values. The pH-values were chosen according to the area of stability of OCP-phase in T-pH space (Figure 1) constructed from both [1] and our own data.

According to XRD, it was shown that HPO_4-anion can be substituted only by succinate-anion to form Suc@OCP. Incorporation of citrate anion in OCP structure didn’t occur apparently due to the odd basicity of the corresponding acid . It was also claimed that the synthesis of Cit@OCP (assuming its existence) requires a lot of time (about 10 days). The processes of thermal decomposition of OCP and Suc@OCP were investigated by thermal and X-ray analyzes. It was suggested that intercalated-OCP is more resistant to thermolysis compared to a pure OCP. Decomposition of “intercalated”-OCP occurs more slowly because of simultaneous liberation of CO_2 and H_2O from the lattice. Heat-treated OCP particles keep their plate-like shape and have no crystallized water being heated to 300°C. An intermediate product of the thermolysis can be described as an apatite-like phase. Ceramics formed from decomposed Suc@OCP have greater shrinkage (≈30%, relative density – 90%) and lower porosity compared to the ceramics made from heat treated OCP (≈15%, relative density – 75%). To create macroporous ceramics the following techniques were tested: the replica method (impregnation of the PU polymer framework by ceramic slurry), the method of removable additives (molding powder together with burning additives, e.g. polystyrene beads) and slip-casting into the plastic molds with special architecture created by FDM 3D-printing (water-based slips as well as paraffin wax thermoplastic slips were used).

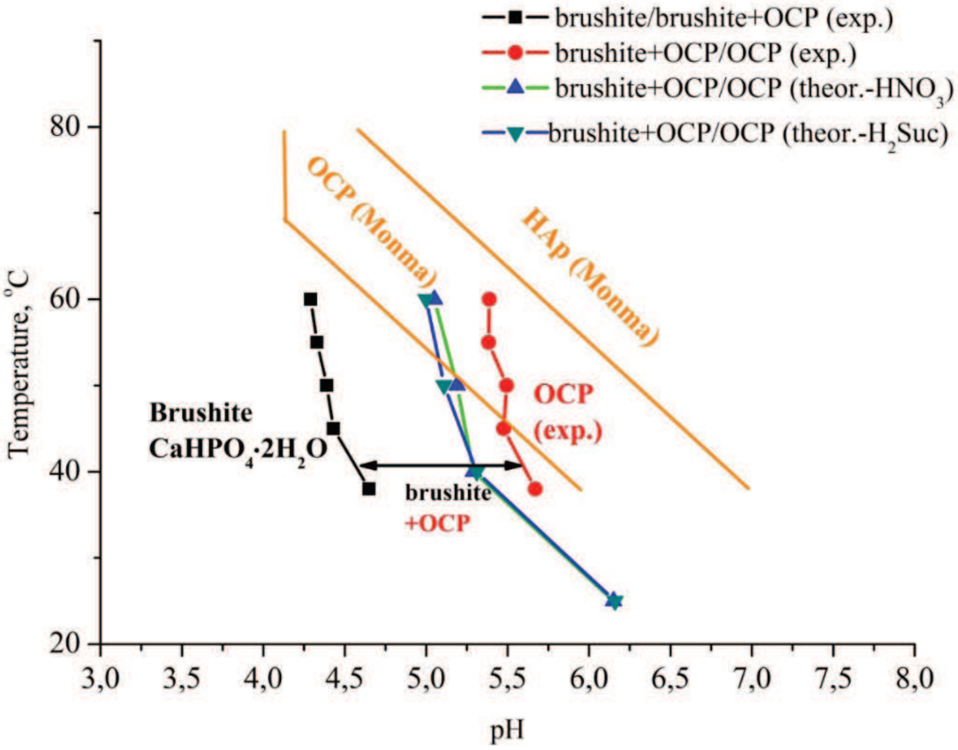

Figure 1: Area of OCP stability in T-pH space (thin solid lines without shapes are related to experimental data on brushite treatment in solutions, according to [1]); our data on hydrolysis of α-TCP in aqueous solutions of nitric and succinic acids are presented as lines with shapes (exp. – our experimental data on pH-titration, theor. – our calculations of ionic equilibria done with HYDRA/MEDUSA and Visual MINTEQ v.3.1).

CONCLUSIONS

Thus, detailed theoretical and experimental studies of ionic equilibria in buffered solution containing brushite or α-TCP were undertaken to determine the area of coexistence of OCP and brushite in T-pH space. These results were used to get the conditions of synthesis of OCP-phases. Various techniques and conditions of solution synthesis have been tested for obtaining of intercalated. The pure product of substitution $Ca_8(HPO_4)_{2-x}R_x(PO_4)_4 \cdot 5H_2O$ (R = Suc) with x = 0,8 ÷ 0,9 was acquired by hydrolysis of α-TCP in the succinic buffer, but the ways to control the degree of substitution x have not been found yet. Suc@OCP demonstrates greater resistance to thermolysis compared to pure OCP. The differences in kinetics and mechanism of their decomposition lead to a different micromorphology of intermediate apatitic product, which is stable up to 630°C in the case Suc@OCP. Variation in phase composition of the thermolysis products leads to the fact that the ceramics based on heat-treated Suc@OCP are denser and apparently stronger than ones based on heat-treated pure OCP. It is shown that slip-casting in 3D-printed plastic forms provides the best reproduction of complex macroporous architecture.

ACKNOWLEDGEMENTS

The work was partially supported by RFBR, grants ##15-03-09387, 16-08-01172. The equipment purchased with the help of the Program of Development of MSU was used.

REFERENCES:

1 Monma, H., Goto, M; Complexes of apatitic layered compound $Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O$ with dicarboxylates. Journal of Inclusion Phenomena, 1 (1984) 127—134.

1ST BIENNIAL CONFERENCE

October 17th-20th
Rome – Italy

ISBN 978 88 8080 214 3