Biomaterials 33 (2012) 5887–5900

Contents lists available at SciVerse ScienceDirect

Biomaterials

journal homepage: www.elsevier.com/locate/biomaterials

Review

Fiber reinforced calcium phosphate cements – On the way to degradable load bearing bone substitutes?

Reinhard Krüger*, Jürgen Groll

University Hospital Würzburg, Dept. Functional Materials in Medicine and Dentistry, Pleicherwall 2, D-97070 Würzburg, Germany

A R T I C L E I N F O

Article history:
Received 16 February 2012
Accepted 23 April 2012
Available online 25 May 2012

Keywords:
Calcium phosphate cement
Fiber reinforcement
Mechanical properties
Load bearing scaffold
In-vivo evaluation

A B S T R A C T

Calcium phosphate cements (CPC) are well-established materials for the repair of bone defects with excellent biocompatibility and bioactivity. However, brittleness and low flexural/tensile strength so far restrict their application to non-load bearing areas. Reinforcement of CPC with fibers can substantially improve its strength and toughness and has been one major strategy to overcome the present mechanical limitations of CPC. Fiber reinforced calcium phosphate cements (FRCPC) thus bear the potential to facilitate the use of degradable bone substitutes in load bearing applications. This review recapitulates the state of the art of FRCPC research with focus on their mechanical properties and their biological evaluation *in vitro* and *in vivo*, including the clinical data that has been generated so far. After an overview on FRCPC constitutes and processing, some general aspects of fracture mechanics of reinforced cementitious composites are introduced, and their importance for the mechanical properties of FRCPC are highlighted. So far, fiber reinforcement leads to a toughness increase of up to two orders of magnitude. FRCPC have extensively been examined *in vitro* and *in vivo* with generally good results. While first clinical products focus on the improved performance of FRCPC with regard to secondary processing after injection such as fixation of screws and plates, first animal studies in load bearing applications show improved performance as compared to pure CPCs. Aside of the accomplished results, FRCPC bear a great potential for future development and optimization. Future research will have to focus on the selection and tailoring of FRCPC components, fiber–matrix compatibilization, integral composite design and the adjusted degradation behavior of the composite components to ensure successful long term behavior and make the composites strong enough for application in load bearing defects.

1. Introduction

Calcium phosphates are established materials for the augmentation of bone defects. They are available as allogenic, sintered or cementitious materials. Unfortunately, these calcium phosphates exhibit relatively poor tensile and shear properties [1]. In practice, the strength of the calcium phosphate cements is lower than that of bone, teeth, or sintered calcium orthophosphate bioceramics [2] and, together with their inherent brittleness, restricts their use to non-load bearing defects [3] or pure compression loading [1]. Typical applications are the treatment of maxillo-facial defects or deformities [4] and cranio facial repair [5] or augmentation of spine and tibial plateau [1].

A successful improvement of the mechanical properties would significantly extend the applicability of calcium phosphates [6] and can be achieved by forming composite materials [7]. Second phase additives to the calcium phosphate composites have been either polymers that interpenetrate the porous matrix or fibrous reinforcements. The composites of calcium phosphates with polymers have been extensively reviewed by several authors (e.g. [3,8,9]): Strength can be improved in such composites but unfortunately, biodegradable polymers, for the most part, lack rigidity, ductility and ultimate mechanical properties required in load bearing applications. Moreover, the typically used sterilization processes (autoclave, ethylene oxide, and ^{60}Co irradiation) may affect the polymer properties.

One of the most successful approaches to toughen brittle materials is the reinforcement with fibers [7]. At the end of the 1980's [10] researchers started to reinforce sintered hydroxyapatite (HA) with different kinds of fibers. Such composites, fabricated by sintering or hot pressing at high temperatures, contain reinforcements that are either morphologically unstable during processing (like HA nano fibers [11,12]), and subsequently lose their toughening effect; or reinforcements that are not bioresorbable, like

* Corresponding author. Tel.: +49 931 201 73710; fax: +49 931 201 73500.
E-mail address: Reinhard.Krueger@fmz.uni-wuerzburg.de (R. Krüger).

0142-9612/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biomaterials.2012.04.053