Available online at www.sciencedirect.com
ScienceDirect
Acta Biomaterialia 4 (2008) 1465–1471
Acta BIOMATERIALIA
www.elsevier.com/locate/actabiomat

Mechanisms underlying the limited injectability of hydraulic calcium phosphate paste

Mohamed Habib [a], Gamal Baroud [a,*], Francois Gitzhofer [b], Marc Bohner [c]

[a] Laboratoire de Biomécanique, Département de Génie, Université de Sherbrooke, Sherbrooke, QC, Canada J1K 2R1
[b] Centre de Recherche en Energie, Plasma et Electrochimie (CREPE), Université de Sherbrooke, Sherbrooke, QC, Canada J1K 2R1
[c] Dr. Robert Mathys Foundation, Bettlach, Switzerland

Received 20 October 2007; received in revised form 10 February 2008; accepted 20 March 2008
Available online 1 April 2008

Abstract

Calcium phosphate (CaP) cements are being increasingly used for minimally invasive hard tissue implantation. Possible approaches to improve the bad injectability of hydraulic calcium phosphate pastes have been discussed and investigated in a number of recent publications. However, the liquid-phase separation mechanism leading to the limited injectability has not yet been addressed. Liquid-phase separation means that the liquid-to-powder ratio (LPR) of the extruded paste is higher than the LPR of the paste left in the syringe. The goal of this paper was to remedy this situation by looking at the liquid-phase migration occurring during the injection of a paste from a syringe through a cannula. Experimentally, it was seen that the liquid content of both the syringe paste and the extrudate decreased during the paste injection. Moreover, a high extrusion velocity, small syringe size, short cannula and high LPR favored a good injectability. These results could be partly explained in light of rheological measurements performed with the investigated paste.

Keywords: Injectable bone substitute; Calcium-phosphate applications; Limited injectability; Experiments

1. Introduction

CaP cements are being increasingly used in minimally invasive interventions to treat fragility fractures [1]. This is due to these cements possessing a number of interesting properties. Namely, their structure and composition resembles human bones, resulting in good biocompatibility and osteoconductivity [2]. In addition, they set practically isothermally compared to acrylic cements [3]. However, they have some critical drawbacks. One of them is their poor ability to be injected through a thin long cannula attached to a syringe, such as in minimally invasive clinical applications [4–6].

The injectability of these cements has been discussed recently in a number of publications (Table 1). There seems to be agreement on the difficulty of injecting cements. However, there is presently no common understanding of the meaning of "injectability". In most research works, injectability has been related to the viscosity of the CaP cement, or in other words to the injection force required to deliver the cement paste, regardless of its quality or homogeneity [5–8]. A recent study conducted by Bohner and Baroud [4] introduced the concept of filter pressing, in which the pressure applied to the cement paste provokes a phase separation after a certain injection time: the liquid comes out without the particles. However, neither the location nor the mechanism of the filter pressing phenomenon was examined. In this study, we focused on the mechanism underlying the limited injectability of CaP cements. First, the uniformity of the extruded cement was studied over the course of the injection to gain a better understanding of the separation forces. In addition, several process parameters, such as liquid-to-powder ratio (LPR), plastic limit (PL), delivery rate and geometry, were investigated.

* Corresponding author. Tel.: +1 819 821 8000x61344; fax: +1 819 821 7163.
E-mail address: Gamal.Baroud@USherbrooke.ca (G. Baroud).

1742-7061/$ - see front matter © 2008 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.actbio.2008.03.004

Table 1
Articles with focus on injectability

Reference	How injectability was studied	Parameters studied						Comments
		LPR	Rheology	PSD	Additives		Process parameter	
[4]	IWP	√		√	Polymeric	Ionic	Cannula diam. and extrusion speed	Analytical model was developed
[5]	Injection pressure				Polymeric	Ionic		
[8]	Injection force				Polymeric			
[6]	IWP	√				Ionic	Time after mixing	
[9]	_		√					
[10]	IWP					Ionic		
[7]	IVP		√		Polymeric	Ionic		
[11]	IWP	√				Ionic		
[12]	IWP				Polymeric			
[13]	IWP					Ionic		
[14]	IWP					Ionic		
[3]	IVP	√	√					Analytical model was examined

IWP, injected weight percentage; IVP, injected volume percentage.

These examinations were done in the light of the filter pressing phenomenon. These results were then compared to force and rheological measurements to understand better the interactions between injection forces, rheological properties and filter pressing.

Instead of using a typical CaP cement suspension, we use a β-tricalcium phosphate (β-TCP) suspension in this study. The main difference between the two is that the CaP suspension sets or cures, whereas the β-TCP suspension does not.

Due to the setting process, the rheological properties of CaP cements are transient and constantly changing. Combined with this is the complication that the injection process may destroy the evolving structure and thereby affect the measurements. Consequently, the results obtained are difficult to interpret.

In contrast, the advantage of the β-TCP suspension is that it allows us to remove the complex curing process and to focus on the properties that are important for injectability. This is especially true since the ideal CaP cement should not react during the injection period. Another advantage is that since β-TCP does not cure, it has a much longer handling time in which experiments can be conducted without time constraints. Additionally, the results obtained are more reproducible.

2. Materials and methods

2.1. Powder characterization

β-Tricalcium phosphate (β-TCP; $Ca_3(PO_4)_2$; Fluka No. 21218) was used as a model powder to investigate the injectability of CaP cements. The β-TCP powder selected here has similar physical properties compared to the β-TCP and α-TCP powders commonly used for CaP cements. As a result, the hydraulic pastes obtained by mixing this specific β-TCP powder with an aqueous solution have similar rheological properties to those of most CaP cement formulations except that the paste does not harden over time. Powders were characterized by various advanced techniques. The particle morphology was examined by scanning electron microscopy (SEM; JSM-840-A JEOL). Particle size distribution (PSD) was determined by laser granulometry (Matersizer 2000, Malvern). For that purpose, powders were dispersed in isopropanol with 0.1% sodium pyrophosphate. Specific surface area was measured with surface area analyzers (Autosorb-1, Quantachrome) following the Brunauer, Emett and Teller theory (BET). The crystalline composition of the powders was determined by X-ray diffraction. The measurements were done on an X'pert Pro MRD (Panalytical) powder diffractometer using a monochromatic source (Cu Kα1, $\lambda = 1.5405980$ Å, 45 kV, 40 mA) in the following conditions: scan range: $2\theta = 5$–70°, scan speed: 0.020° s^{-1}, scan step: 0.020°). The different phases present in the powders were checked by means of JCPDS (Joint Committee on Powder Diffraction Standards) references patterns (β-TCP: JCPDF 9-169; α-TCP: JCPDF 29-359; HAP: JCPDF 9-432; TTCP: JCPDF 25-1137; CaO: JCPDF 37-1497).

The PL was determined according to the procedure described by Bohner and Baroud [4], in which the PL is obtained by measuring the minimum amount of liquid that has to be added to a powder to form a paste. PL is expressed in milliliters per gram.

The rheological tests were conducted by using a TA rheometer (TA Instrument). Ionized water was used as an aqueous media to make the suspension. Three different LPR values were used (40, 50 and 65 wt.%). After 1 min of mixing, the suspension was transferred immediately into the concentric geometry rheometer. Each sample was subjected to a flow procedure with a shear rate peak hold. Shear rate was held at different values starting from 0.002 [1/s] to 100 [1/s]. At each hold value of the shear rate, both viscosity and shear stress values were collected. Curves were plotted of the viscosity and the shear stress vs. the shear rate.

ID	Title	Pages
1579	Mechanisms underlying the limited injectability of hydraulic calcium phosphate paste	7