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Research paper

Ceramic cement as a potential stand-alone treatment for bone fractures: An in vitro study of ceramic–bone composites

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ABSTRACT

Background: A vertebral burst fracture (VBF) treated with vertebroplasty using a ceramic cement consists of four regions; native bone fragments, native ceramic cement, ceramic cement–trabecular bone (ceramic–bone) composite and ceramic–bone interface. Although the mechanical properties of native bone and native ceramic cements have been well investigated, the mechanical properties of ceramic–bone composite and ceramic–bone interface remain unknown. Therefore, the aim of this study was to determine the mechanical properties of ceramic–bone composites and ceramic–bone interfaces. Two types of ceramic cement, calcium aluminate (CAC) with (w/F) and without (wo/F) fiber reinforcement, were investigated.

Methods: Ceramic–bone composite (Full, wo/F and w/F) and ceramic–bone interface (Fract, wo/F and w/F) groups were tested to determine their compressive and tensile properties. While a continuous bone cylinder was used for samples in the Full groups, each bone cylinder for the samples in the Fract groups contained a 3 mm geometrical discontinuity to mimic the fracture gaps in VBFs. Two Cement groups (wo/F and w/F) and a Bone group were included in the study as controls. Micro-CT images were used to determine the bone morphological parameters, as potential predictors of the mechanical properties of Full and Fract groups.

Results: The compressive strengths of Full and Fract groups were substantially lower than native CAC, but higher than bone. The tensile strength of the Full group was equal to bone, while the tensile strength of the Fract group was equivalent to CAC. Variable relationships between the bone morphological parameters and mechanical properties of Full and Fract groups were observed. Fiber reinforcement at an injectable level had a minimal influence on the mechanical properties.

Conclusions: CAC augmentation does not provide adequate stabilization of bone fragments.

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The interface between bone and cement represents a weak point. The effect of cement augmentation cannot be predicted by bone morphological properties.

1. Introduction

The first clinical use of percutaneous vertebroplasty (PVP) as a stand-alone treatment for stable vertebral burst fractures (VBFs) was reported in 2004 (Chen and Lee, 2004). Since then, an increasing number of successful clinical implementations of PVP for VBFs have been reported (Chen and Lee, 2004; Tender and Serban, 2012; Amoretti et al., 2005; Shin et al., 2009; Doody et al., 2009). These studies highlight the positive clinical outcomes of reduced pain (Chen and Lee, 2004; Tender and Serban, 2012; Amoretti et al., 2005; Shin et al., 2009; Doody et al., 2009) and morbidity (Tender and Serban, 2012). The most frequently used material for PVP is PMMA (Chen and Lee, 2004; Tender and Serban, 2012; Amoretti et al., 2005; Shin et al., 2009; Doody et al., 2009). Although PMMA possesses excellent mechanical properties, its suboptimal biological properties (e.g. high setting temperature and residual monomer toxicity) (Hu and Hart, 2007) raise concerns about the long term viability of PMMA treated VBFs. Contrary to PMMA, calcium-based ceramic cements (e.g. calcium sulfates and calcium phosphates) exhibit the desirable biological properties of bioresorbability, osseointegration and osteoconductivity (Giannoudis et al., 2005). However, the mechanical response of VBFs treated using ceramic cements was found to be significantly inferior to that of intact or PMMA treated vertebrae (Wu et al., 2007; Tarsuslugil et al., 2014). Moreover, these ceramic cements were found to resorb at different rates in vivo (Barinov and Komlev, 2011), raising questions about their ability to provide adequate immediate and long term mechanical stabilization of bone fragments in VBFs. Therefore, a biocompatible ceramic cement exhibiting outstanding mechanical properties without in vivo resorbability (e.g. calcium aluminate (Engqvist et al., 2008; Garcia et al., 2014)) can be considered as a potential alternative, providing a permanent solution to provide the required mechanical stability to the treated VBFs.

Four regions with distinctly different mechanical properties exist in ceramic cement treated VBFs: 1) native trabecular bone fragments, 2) ceramic cement, 3) ceramic cement–trabecular bone (ceramic–bone) composite, and 4) ceramic–bone interface (Fig. 1). The mechanical properties of ceramic–bone composites and ceramic–bone interfaces are especially interesting due to their possible independence from the bone morphological parameters (Kinzl et al., 2011; Helgason et al., 2013) and the need to withstand high tensile stresses developed under physiological loading conditions (Koh et al., 2013) respectively. Inadequate mechanical properties (e.g. strength) in any of the four regions may lead to poor immediate stabilization of ceramic cement treated VBFs, resulting in an early onset of failure, especially under the influence of complex, multi-axial spinal loading. Therefore, the ability to predict the mechanical properties of each of the four regions would be a valuable step towards the development of ceramic cements for the stabilization of VBFs.

The mechanical properties of trabecular bone can be predicted using local bone density and anisotropy (Morgan et al., 2003). The mechanical properties of ceramic cements, on the other hand, vary depending on their formulation (Zhang et al., 2014). General consensuses on the mechanical properties of ceramic cements is that they are brittle (Zhang et al., 2014) with inferior tensile and shear strength compared to PMMA (Dorozhkin, 2010; Morgan et al., 1997; Zhang et al., 2011). Considering the bending and torsional loads applied to the spine, the tensile strength of the cement may be a deciding factor for the successful reduction and stabilization of bone fragments. Fiber reinforcement has been suggested as a means to improve the tensile properties (Zhang et al., 2014). Fiber reinforced ceramic cements can exhibit improved tensile strength, flexural strength and work to failure (Burguera et al., 2005; Maenz et al., 2014; Xu et al., 2000). Despite these improvements in the mechanical properties of ceramic cements, the use of fiber reinforced ceramic cement to treat VBFs has not been investigated. The mechanical properties of the ceramic–bone composite and ceramic–bone interface regions are unknown. The mechanical properties of PMMA-bone composites are found to be independent of the bone morphological parameters, but dependent on the porosity of PMMA in PMMA-bone composites and the mechanical properties of the injected PMMA (Kinzl et al., 2011; Helgason et al., 2013; López et al., 2014). The mechanical properties of the PMMA-bone interface are determined by the amount of bone interdigitated with PMMA (Mann et al., 2008, 1997). These imply possible differences in the mechanical properties of ceramic–bone composites and ceramic–bone interfaces. Thus, investigations on the mechanical response of ceramic–bone composites and ceramic–bone interfaces must be performed independently.

Therefore, the overall goal of the study was to investigate the mechanical properties of ceramic–bone composites and ceramic–bone interfaces. Two specific aims were defined: 1) to determine the tensile and compressive mechanical properties of bone augmented with ceramic cement, with and without a simulated fracture plane, and 2) to determine the correlation between the morphological parameters of the bone and the mechanical properties of ceramic–bone composites and ceramic–bone interfaces. Two different types of calcium aluminate cement (CAC, with and without fiber reinforcements) were used to investigate the effect of fiber reinforcement on the mechanical properties of ceramic–bone composites and ceramic–bone interfaces.

2. Methods

2.1. Design of the study

Seven groups were tested in two loading modes (compression and tension). The groups were divided into native bone