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Mechanical characterisation of three percutaneous vertebroplasty biomaterials

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Abstract Percutanous vertebroplasty (PVP) is gaining popularity for the treatment of vertebral compression fractures. The need of obtaining low viscosity materials for injection through small bore needles and the necessity of visualising the fluid flow during injection have led users to the formulation of a number of ad-hoc recipes aimed at adapting PMMA cements for this use. Industry, on its part, has addressed these requirements by developing specific products for this application.

This study aimed at providing a direct comparison of a wide range of mechanical properties between three commercially available biomaterials developed for PVP: two PMMA based materials, Osteopal V (Merck Biomaterial GMBH, Dermstedt, D) and Verterbroplastic (DePuy Acromed, Inc, MA, USA), and a Bis-GMA composite, Cortoss (Orthovita, PA, USA). Cortoss consistently exhibited higher values for compressive strength, bending modulus and shear strength to both Osteopal V and Vertebroplastic. The creep behaviour of Cortoss was also different from that of the two PMMA cements.

PVP can take advantage from the development of new injectable biomaterials in response to the problems associated with the use of PMMA in a highly vascularised area such as the vertebral body. In addition careful modulation of the mechanical properties of the material has the potential to further improve the outcome of PVP, possibly reducing the risk of adjacent level fractures associated with the procedure.

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1. Introduction

Vertebral compression fractures affect a significant number of people and the incidence continues to grow at an alarming rate. Osteoporosis is by far the most likely cause of vertebral compression fractures. It has been estimated that of the 700,000 osteoporotic vertebral compression fractures diagnosed in the US each year 260,000 are symptomatic, respond poorly to conservative treatment and half of these require hospital admission. This number is predicted to increase by a factor of four in the next fifty years [1].

Vertebral compression fracture management aims at restoring the mechanical stability and balance of the spinal column, improving optimal neurological function and minimizing morbidity associated with whatever treatment has been preferred [2].

Percutaneous vertebroplasty, a procedure originally developed for the treatment of angiomas [3], fulfils these requirements and has gained much popularity for the treatment of vertebral compression fractures (VCFs), due to its capability to relieve pain. Percutaneous vertebroplasty (PVP) is a minimally invasive technique consisting in the injection of a low viscosity biomaterial into the vertebral body through a cannula inserted via the pedicle. The procedure is performed under local anaesthetic. The injection of the material is monitored in real time with fluoroscopic visualisation. In most cases the patient is discharged on the same day of treatment [4].

PVP is associated with significant and immediate pain relief in at least 75% of the cases [4–6]. The mechanisms underlying this pain relief are not fully understood, but probably involve mechanical or neurological factors or a combination of the two [7, 8]. The clinical benefit appears to be long lasting with the pain reduction at one month persisting at longer follow-up periods of up to 48 months [5].

Complications reported for the treatment of vertebral compression fractures with vertebroplasty include: failure to improve symptoms or increased pain, pulmonary embolism, fracture of adjacent vertebrae, radiculopathy and spinal cord compression [4–6, 9, 10]. In most cases these amount to a complication rate of less than 10% which is further reduced to 1% when the compressive fractures are a consequence of osteoporosis [8, 10]. Extravasation of the cement from the vertebral body is often reported but, in the vast majority of cases, it appears to be inconsequential [5, 6].

While the optimal set of mechanical properties for vertebroplasty biomaterials are yet to be finalised, it has been noted that the most appropriate biomaterial would ideally be a bio-active, slowly resorbable cement, capable of restoring the mechanical properties of the treated vertebrae to levels comparable to those of healthy vertebrae. Ability to provide immediate reinforcement of the vertebral body so to allow early ambulation is also desirable [11]. A significant amount of effort has gone into adapting existing PMMA based cements for vertebroplasty applications. The orthopaedic community avails itself of more than forty years experience in the use of PMMA bone cements, in this light the transition from arthroplasty to vertebral augmentation appears almost natural. The constraints imposed on the materials by vertebroplasty, such as having to inject the cement into the vertebral body through small bore needles and the necessity of being able to clearly visualise very small volumes of material, have led users to the formulation of a number of *ad-hoc* recipes for this application. The viscosity of standard bone cements is modulated by increasing the liquid to powder ratio. This practice has the known effect of ultimately decreasing the mechanical properties of the cured polymer and significant effects on the compressive strength have been reported in the literature [12, 13]. A greater liquid to powder ratio results in an increase in maximum temperature, setting time and dough time of the cement [12, 15]. The total amount of monomer present in the mixture is increased and the relative concentration of the initiator of polymerisation contained in the powder is reduced [12]. Sizeable quantities of various additives, such as barium sulphate, zirconium dioxide and powdered tantalum or tungsten, are used to improve the low radiopacity of standard cements [4–6, 10, 12, 14, 16]. The addition of opacifiers in liquid form has also been reported [17]. This practice can significantly reduce the mechanical properties of the base material as radiopacifiers do not take part in the polymerisation reaction and introduce defects in the materials matrix that can act as stress risers [12].

This study aimed at providing a direct comparison in terms of a wide range of mechanical properties between three commercially available biomaterials specifically developed for vertebroplasty application.

2. Materials and methods

The compressive strength, bending strength and bending modulus, shear strength and creep behaviour of three biomaterials for use in vertebroplasty were evaluated. The properties of two polymethylmethacrilate based biomaterials, Osteopal V (Merck Biomaterial GMBH, Dermstedt, D) and Verterbroplastic (DePuy Acromed, Inc, MA, USA), were compared to those of Cortoss (Orthovita, PA, USA), a Bis-GMA composite.

The polymethylmethacrylate composites were mixed in a bowl following the manufacturers instructions: the full contents of one pouch of PMMA powder were added, in a cement mixing bowl (Ultramix, Summit Medical, Ltd, UK), to the contents of one ampoule of monomer. The mixture was slowly stirred to avoid entrapment of air with a stainless steel spatula until the liquid had completely wetted the powder. After stirring for 30s the mixing bowl was covered in order to prevent monomer evaporation and the mixture was allowed to rest for two min. The cement was then slowly stirred for an additional 5s prior to use. The delivery phase for each of the PMMA cements started two and a half min after the powder and liquid component first came into contact. Cortoss, the only Bis-GMA material in this study, was mixed using the proprietary in-syringe mixing system. Care was taken to ensure that both constituting resins were extruded at equal rate from each cartridge compartment. The manufacturer requires that Cortoss is stored in a fridge between 2–8°C, this practice increases the viscosity of the cement. To facilitate extrusion from the mixing nozzle, Cortoss was conditioned at room temperature for at least one hour prior to use. In the case of Cortoss there was no time delay between the time of mixing and the time of delivery.

2.1. Compressive strength

The compressive strength of the three materials was evaluated following the method described in ISO 5833: 2002 Annexe E [18]. Five cylinders of 6 ± 0.1 mm diameter and 12 ± 0.1 mm height were prepared for each material investigated. The cylinders were conditioned in air at 23 ± 1°C and were tested in compression on a servohydraulic universal testing machine (Dartec HC 10, UK) 24 ± 2 hours after the mixing of the cement begun. The cross-head speed of the machine was 19.8 mm/min. For each cylinder the maximum force applied, or the 2% offset load or the upper yield point, whichever occurred first, were recorded. The compressive strength was calculated as the ratio between the applied load and the cross sectional area of the specimen.

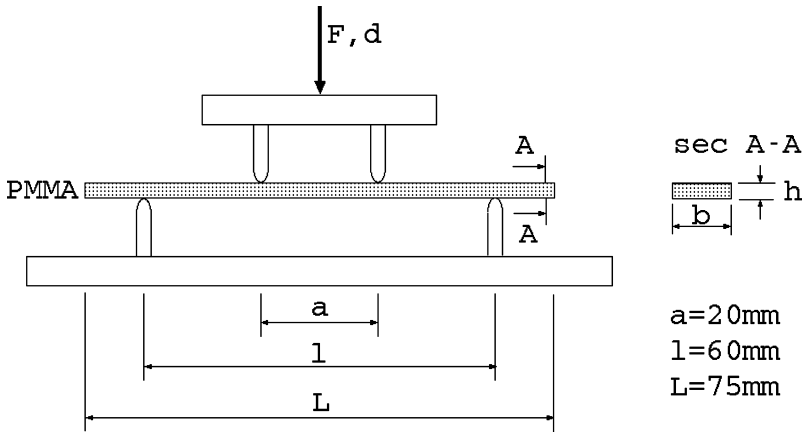

Fig. 1 Four point bending test arrangement.

2.2. Bending strength and bending modulus

The bending strength and bending modulus were evaluated with the four point bending method described in ISO 5833: 2002 Annexe F [18]. Five rectangular test specimens of 75 ± 0.1 mm length, 10 ± 0.1 mm width and 3.3 ± 0.1 mm depth were produced for each material and conditioned in air at 23 ± 1°C for 24 ± 2 hours prior to testing. Each specimen was mounted in a four point bending rig (Figure 1) fitted between the crosshead and baseplate of a servohydraulic testing machine (Dartec HC10, UK) and tested to failure. The crosshead speed of the machine was 5 mm/min. The bending modulus and bending strength were calculated for each specimen following the method outlined in ISO 5833:2002 [18].

2.3. Shear strength

Four cylindrical test specimens of 8.0 ± 0.1 mm diameter and 20mm length were produced for each material and conditioned in air at 23 ± 1°C for 24 ± 2 hours prior to testing. Each specimen was mounted in a shear rig fitted between the crosshead and baseplate of a servohydraulic testing machine (Dartec HC10, UK) and tested to failure. The crosshead speed of the machine was 5 mm/min. For each cylinder the maximum force applied, or the 2% offset load or the upper yield point, whichever occurred first, were recorded. The shear strength was calculated as the ratio between the applied load and the cross sectional area of the specimen.

2.4. Static creep behaviour

Static creep was evaluated by means of a four point bending rig applying a constant load to each of the beams. A custom multistation creep rig has been developed to enable four point bending creep experiments to be carried out in a water bath at body temperature (Fig. 2). Six rectangular test specimens of 75 ± 0.1 mm length, 10 ± 0.1 mm width and 3.3 ± 0.1 mm depth were produced for each material and conditioned in saline at 37 ± 1°C for 48 ± 2 hours prior to testing. The specimens were mounted in the creep rig and their deformation under a constant load, producing a maximum nominal stress of 8 MPa in the centre of the beam, was recorded over a period of three days. Throughout the course of the test the specimens were immersed in a distilled water bath kept at a constant temperature of 37°C. Differences in the deflections of the different materials were evaluated at six different time points, namely one, three, six, twelve, twenty-four and seventy-two hours from the start of the experiment.

2.5. Statistical analysis

All results are presented as mean ± standard deviation. Differences between the groups were examined using Analysis of Variance (ANOVA) with SPSS v11 statistical software (SPSS Inc., Chicago, IL, USA). Significant main effects determined by ANOVA were further investigated with the Bonferroni post-hoc test. Differences between the groups were considered statistically significant if P was less than 0.05.

3. Results

The compressive strength of Cortoss (146 ± 18 MPa) was significantly higher than that of Osteopal V (82 ± 3 MPa) and Vetebroplastic (70 ± 4 MPa) (Fig. 3). These differences were statistically significant (P = 0.000 in both cases). There was no difference between the compressive strength of Osteopal V and Vertebroplastic cements.

Cortoss exhibited a bending strength of 57 ± 10 MPa, Osteopal V of 46 ± 8 MPa and Vertebroplastic of 45 ± 5 Mpa

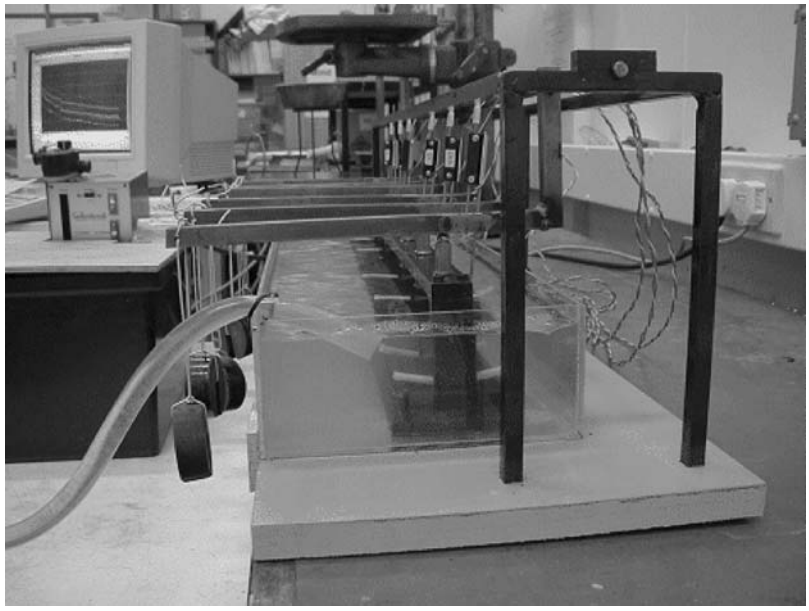

Fig. 2 Multistation four point bending creep rig.

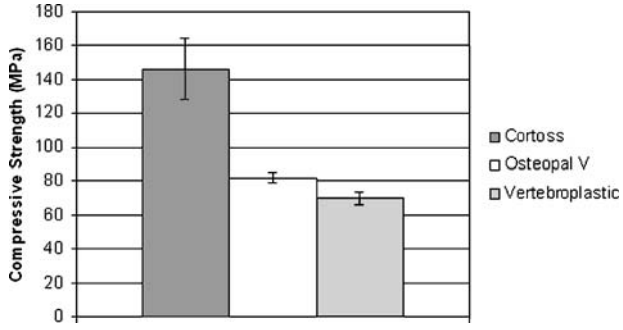

Fig. 3 Mean compressive strength and standard deviation for Cortoss, Osteopal V and Vertebroplastic.

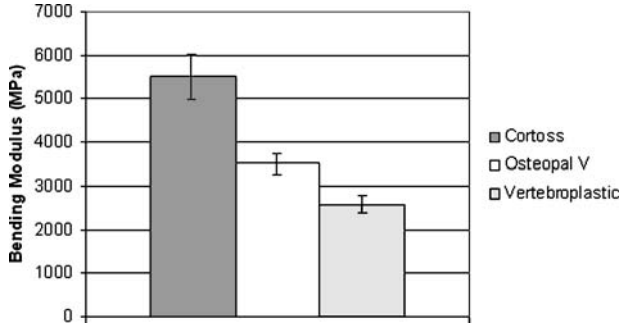

Fig. 5 Mean bending modulus and standard deviation for Cortoss, Osteopal V and Vertebroplastic.

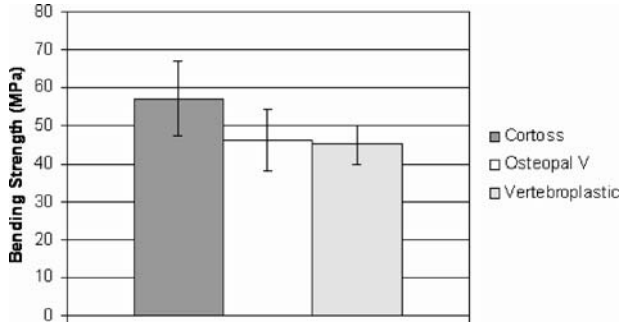

Fig. 4 Mean bending strength and standard deviation for Cortoss, Osteopal V and Vertebroplastic.

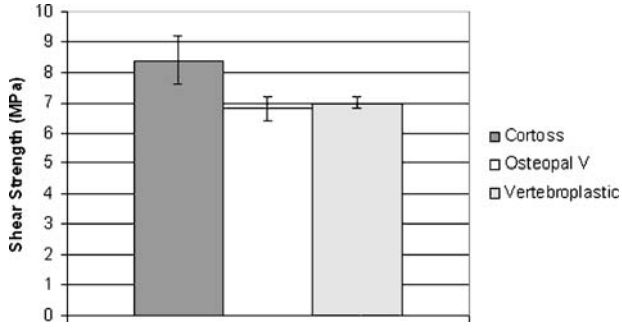

Fig. 6 Mean shear strength and standard deviation for Cortoss, Osteopal V and Vertebroplastic.

(Fig. 4). These differences were not statistically significant. The bending modulus of Cortoss (5505 $\pm$ 509 MPa) was significantly higher than that of Osteopal V (3504 $\pm$ 235 MPa, $P = 0.000$) and that of Vertebroplastic (2574 $\pm$ 199 MPa, $P = 0.000$) (Fig. 5). Differences between Osteopal V and Vertebroplastic were also statistically significant ($P = 0.003$).

The shear strength of Cortoss (8.4 $\pm$ 0.8 MPa) was significantly higher than that of Osteopal V (6.8 $\pm$ 0.4 MPa, $P = 0.002$) and Vertebroplastic (7.0 $\pm$ 0.2 MPa, $P = 0.005$) (Fig. 6). Differences between the two PMMA bone cements were not statistically significant.

The static creep deformations induced in the PMMA based cement and Cortoss under the same loading conditions

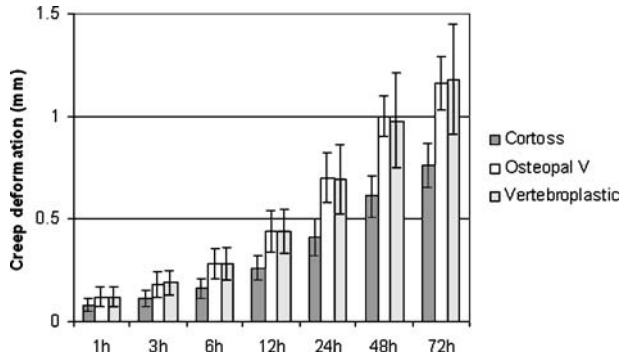

Fig. 7 Static screep deflection induced by a constant stress of 8MPa for Cortoss, Osteopal V and Vertebroplastic at different time intervals.

became significant in the first few hours of testing (Fig. 7). A nominal stress of 8MPa applied for one hour induced a deflection of 0.08 ± 0.03 mm in the case of Cortoss and 0.12 ± 0.05 mm in the case of Osteopal V and Vertebroplastic, these differences were not significant. After 3 hours the deflections increased to 0.11 ± 0.04 mm for Cortoss and 0.18 ± 0.06 for Osteopal V and 0.19 ± 0.06 for Vertebroplstic, respectively. These differences were not significant. For each of the following time points the deflection induced in Osteopal V and Vertebroplastic were significantly greater than those induced in Cortoss. At 72 hours the deflection induced in Cortoss beams was smaller than that of the two PMMA cements, 0.76 ± 0.11 mm compared to a mean deflection in Osteopal V beams of 1.16 ± 0.13 ($P = 0.10$) and in Vertebroplastic beams of 1.18 ± 0.27 mm ($P = 0.007$). The two PMMA bone cements crept at the same rate.

4. Discussion

This study has shown that there are statistically significant differences in the mechanical behaviour of the three materials investigated. In particular, Cortoss consistently exhibited higher values for compressive strength, bending modulus and shear strength to both Osteopal V and Vertebroplastic. The creep behaviour of Cortoss was also different from that of the two PMMA based cements. These discrepancies were not unexpected given the different chemical composition of the three materials tested in this study.

Osteopal V and Vertebroplastic are PMMA based bone cements while Cortoss is a composite thermoset biomaterial. Cortoss comprises three main resins: two high viscosity, high molecular weight and highly cross-linked matrix resins, Bis-GMA (2, 2-bis[4-(2-hydroxymetacryloxypropyl) phenyl]propane) and Bis-EMA (2, 2-bis[4-(2-methacryloxyethoxy)] phenylpropane), and a viscosity modifier, TEGDMA (triethylene glycol dimethacrylate) [19]. Bis-GMA based biomaterials, originally developed as substitutes for PMMA in dental applications, have often been found to exhibit improved strength with respect to PMMA cements [20, 21]. In addition Cortoss contains reinforcing particles of silica, barium boro-aluminosilicate glass and combeite glass ceramic.

The magnitude of the difference in mechanical properties between Osteopal V and Vertebroplastic was unexpected but could, to an extent, be explained in terms of their different compositions. Vertebroplastic is characterised by an increased monomer to polymer ratio compared to Osteopal V. Changes of this parameter have the known effect to decrease the mechanical strength of the polymerised material [12, 13].

5. Conclusions

PVP can take advantage from the development of new bone cements in response to the problems associated with the use of PMMAs in a highly vascularised area such as the vertebral body. Factors that need be taken into account include low polymerisation temperature, suitable viscosity at the time of injection, mechanical compliance and good osteoconductivity. This study has characterised the properties of three commercially available materials suitable for PVP applications in terms of compressive strength, bending strength and bending stiffness, shear strength and static creep. The mechanical strength attained by the vertebrae after treatment might play a significant role in the load transfer from one level to the next. Careful modulation of the mechanical properties of the material to be injected has the potential to further improve the outcome of PVP, possibly reducing the risk of adjacent level fractures associated with the procedure [5]. Anecdotal evidence from the current literature indicates that percutaneous vertebroplasty provides effective pain relief for compression fractures [4, 5, 6]. Ultimately, whether PVP is more effective than traditional treatment regimes needs to be addressed by long-term prospective randomised controlled trials which are currently under way both in Europe and Australia [22].

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