Biomechanical Efficacy of PMMA as a Bone Cement in Vertebral Repair and Reinforcement

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INTRODUCTION

Vertebral fractures are the most common age-related osteoporotic fracture, and they occur at a frequency of 700,000 annually in the United States alone1. A noninvasive surgical treatment recently introduced for the repair of these fractures is percutaneous vertebroplasty, which involves fortification of the osteoporotic vertebral body with an injected bone cement, polymethylmethacrylate (PMMA). This procedure has also been recently proposed for use as a preventive measure to minimize the risks for fractures2. However, despite success in enhancing the mechanical properties of the augmented vertebral body, little is known whether the structural behavior improvements are truly beneficial or do they exacerbate the condition. Recent studies have suggested that PMMA filling may possibly promote fractures in the adjacent vertebrae due to the sharp increase in stiffness of the augmented vertebra3, 4. The goal of this study was to determine the biomechanical efficacy of the bone cement PMMA in vertebral repair and reinforcement using a combinatorial approach with biomechanical experiments and anatomically detailed computer models. Our specific aims were to: 1) determine the effects of PMMA augmentations on stiffness and strength in a damaged vertebra, and 2) in an undamaged vertebra.

METHODS

A finite element model of a human vertebral body (L3, female, age = 76 years) was generated from quantitative computed tomography (QCT) scans. Trabecular bone properties were assigned based on QCT densities. Cortical tissue properties were calibrated to experimental results obtained from uniaxial compression testing of the same vertebral body5. The specimen was placed between steel platens on a screw-driven load frame (Instron Corporation, Model 5583, Canton, MA) and loaded monotonically in displacement control at a rate of 0.15 mm/sec (~0.5 % strain per second). Two models of an intact and fractured vertebra were developed. Damage of the vertebra was modeled by reducing the elastic moduli of the yielded trabecular elements based on total strains6 and for the cortical elements, a perfect damage model was utilized.

Bipedicual vertebroplasty approach was simulated using the finite element model (see Fig. 1). Four different PMMA volumes corresponding to approximately 5%, 10%, 15% and 20% fill of PMMA to whole vertebral body volume were modeled. The stiffness and strength of the virtually treated vertebra under uniaxial compression were predicted for vertebral repair (damaged model) and reinforcement (undamaged model) for all the four cases using the finite element solver ABAQUS. The increases in strengths relative to initial strength values were plotted against the increases in stiffness relative to initial stiffness values.

RESULTS

The application of bipedicular vertebroplasty towards the repair of the damaged vertebral body led to a 68% increase in compressive strength for the same relative increase in stiffness. This indicated that the stiffness increased at a faster rate than strength with PMMA augmentation. Similar procedure replicated on the undamaged model to simulate prophylactic treatment resulted in an increase in compressive vertebral strength that was proportional to the increase in stiffness (see Fig. 2).

DISCUSSION

This study investigated the biomechanical efficacy of using PMMA as a bone cement in vertebroplasty for repair of damaged vertebra and reinforcement of vertebra at risk of fracture. Our findings demonstrated a 47% higher increase in stiffness with increases in compressive strength for the repair of damaged vertebra with PMMA.

Fig. 1. Finite-element mesh with two PMMA capsules (shaded) simulating bipedicual vertebroplasty approach.

Fig. 2. Normalized compressive strength (divided by initial strength) versus normalized stiffness (divided by initial stiffness) of a vertebral body after a) repair and b) reinforcement by bipedicual approach. Initial values for undamaged and damaged models correspond to intact and initial damaged values. The three fracture risk groups were defined by Biggeman et al.7. P = pre-damage values for stiffness and compressive strength.

Restoration of compressive strength to pre-damage values (2.4 kN from 1.2 kN) was achieved with 20% fill of PMMA. Improvement of strength to low fracture risk levels (>5 kN) would restore stiffness to pre-damaged values (8.4 kN/mm from 1.5 kN/mm). However, this would require a much larger PMMA volume than 20%, which would raise the risk of cement leakages into surrounding tissue, causing further complications. Therefore, PMMA may not be the best material for use in vertebroplasty for the treatment of vertebral fractures with severe mechanical property loss.

For vertebral reinforcement, PMMA affected equivalent increases in stiffness and strength. Improvement of strength to low fracture risk levels would result in an increase of stiffness from 8.4 kN/mm to 17.2 kN/mm. The significant raise in stiffness could lead to drastic changes in the dynamics of the vertebrae and may cause even more fractures. Further investigation of other materials for use in vertebroplasty is therefore required.

The combined experimental-computational approach allows multiple analyses of the same specimen after various different treatments, and is also able to overcome problems associated with biological heterogeneity in vertebral geometry and bone density.

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REFERENCES


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