Mechanical Strength of Radius Fracture Repair Using an Expanding Cement

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Introduction

Displaced fractures of the distal radius are typically repaired by either closed reduction and casting or open reduction with internal plate fixation. This treatment dichotomy fails for elderly patients, where risks associated with open surgery outweigh benefits, and malunions after closed reduction frequently result in deformity. A need exists for minimally invasive fixation which provides the benefits of internal fixation without associated surgical risks. Efforts have been made to utilize materials such as acrylic cements (PMMA) and hydroxyapatite based cements (HAC) to anchor the trabecular bone on either side of a fracture. Despite promising results, the approaches were plagued by material limitations including lack of bone ingrowth and integration (PMMA) and inadequate mechanical properties (HAC) [1]. A castor oil based polyurethane cement may prove a suitable alternative as it demonstrates mechanical properties akin to cancellous bone, porosity requisite for bone ingrowth and integration, and an opportunity for enhanced mechanical fixation through volumetric expansion during curing. The objective of this work was to experimentally evaluate the mechanical strength obtained in radius fracture repair with a castor oil based polyurethane material and compare the results to similar fixation with PMMA. We hypothesized that the castor oil based cement would provide superior mechanical strength relative to a similar PMMA repair.

Methods

Six pairs of fresh-frozen human radius samples were cleaned of soft tissue and cut to isolate the distal and proximal ends (3 male, 3 female, mean age 65, range 38 – 83). Distal ends underwent microCT scanning at 38 µm resolution and were analyzed for preexisting pathologies, total bone volume fraction, trabecular morphology, and bone density. All specimens were potted and transverse cuts were made at 10% (of the overall bone length) from the distal or proximal end to simulate fractures. The use of proximal ends eliminated the need for six additional donors to obtain purely distal specimens. Radius pairs (right/left) were divided into two groups: PMMA (Simplex P. Stryker, Mahwah, NJ) or the castor oil based cement (Kryptonite Bone Cement, Doctors Research Group, Inc., Southbury, CT). Materials were mixed and pasted onto both sides of the cut surface of a sample. Specimens were re-apposed and positioned to simulate fractures. Distal specimens were placed with the volar surface facing the loading platens. A point load was applied at 0.1 mm/s, creating a shearing force and bending moment across the cut surface (Fig 1). Peak shear and bending stress were calculated using beam theory. Proximal specimens were positioned vertically and distracted at 0.1 mm/s (Fig 1). Average tensile failure stress was calculated. Data were analyzed using paired t-tests (right vs left).

Results

No gross abnormalities or differences between right and left limbs were detected via micro CT. Apparent bone density of the trabecular compartment were 107.7±50.4 g/cm² and 110.7±52.1 g/cm² for castor oil based cement and PMMA groups, respectively. Trabecular thickness was 141.3±26.5 µm and 143.6±22.2 µm; total bone volume fraction was 9.4±4.7 % and 9.7±4.7 % in the two groups, respectively.

In the shear/bending configuration, failures appeared to be tensile at the Volar surface due to the bending moment as opposed to a pure shear failure, with strengths significantly elevated in the castor oil cement group (Table 1). Within the castor oil cement treated samples, 3 samples failed within the cement, with material remaining secured to either side of the defect. The remaining 3 samples failed in the bone, with 2 failures of neighboring trabecular bone and one failure of the cortical shaft. Not surprisingly, the bone failures were in samples of poorer bone density. The PMMA failures were primarily at the cement-bone interface. Two of the 6 failures also incorporated a small region of trabecular bone failure.

Proximal radius specimens tested in tension failed primarily at the distal cut surface, with no significant difference detected between groups (Table 1). All PMMA samples failed at the cement-bone interface. A small amount of trabecular bone fractured and remained attached to the material in 2 samples. Samples treated with the castor oil based cement underwent a partial material failure within each sample, with residual material remaining on both cut surfaces. Partial cancellous bone fracture was observed.

Linear correlations between predictor bone quality measures (volume fraction, etc.) and fixation strength were not detected via Pearson's correlation coefficients (p<0.05 for all).

Discussion

Cement-based fixation demonstrates promise for treatment of pathologic fractures such as an osteoradionecrosis related fracture of the radius. The use of PMMA as a fixator has a clinical past with excellent functional and cosmetic results [2], though has failed to gain widespread acceptance primarily due to a lack of long term bone ingrowth and material integration. The test data presented here demonstrate a biomechanical superiority of the polyurethane cement as a means for fixation, and thus it is reasonable to expect functional outcomes rivaling those previously reported. Additionally, the porous polyurethane offers the unique advantage of integration with ingrowing bone [3], indicating a possibility for long term integration and stability, overcoming a major shortcomings of the PMMA approach.

The superior mechanical properties of the castor oil based cement repairs is likely multifactorial. Penetration of the polyurethane cement into the trabecular network, driven by a volumetric expansion during curing, was likely a primary factor in the observed strength by forcing enhanced inter-digitation and mechanical interlock. Qualitative observation confirmed deeper penetration of the urethane cement into the trabecular bone relative to the PMMA, and additional laboratory experimentation confirmed a 30% increased penetration depth by the castor oil based cement relative to an acrylic cement (Fig 3). An additional factor is a potential reduction in stress concentrations in specimens fixed with castor oil derived cement versus PMMA, which though not incorporated into this model likely factored into the observed failure modes. Acrylic cement is stiffer than the bone with which it is interacting, whereas the polyurethane provides a closer match in material properties. A reduction in stress concentration and stress shielding may have a beneficial impact in neighboring bone health as well as compressive strength of the repaired limb.

The potential treatment using this cement-based fixation strategy offers promise in reducing morbidity associated with distal radius fracture in the elderly. Ultimately the approach adopted in this study of open reduction and fixation must be converted to a minimally invasive approach to attain clinical utility as an alternative to fracture fixation.

References


Acknowledgements

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Table 1 – Calculated Failure Stress; † indicates p=0.05

<table>
<thead>
<tr>
<th></th>
<th>AVG Shear Stress (MPa)</th>
<th>Peak Bending Stress (MPa)</th>
<th>AVG Tensile Stress (MPa)</th>
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<tbody>
<tr>
<td>Kryptonite</td>
<td>0.911 ± 0.203 †</td>
<td>2.568 ± 0.898 †</td>
<td>0.834 ± 0.380</td>
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<tr>
<td>PMMA</td>
<td>0.314 ± 0.273</td>
<td>1.020 ± 0.939</td>
<td>0.744 ± 0.226</td>
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AVG = Average; † indicates p<0.05 for all

Table 2 – MicroCT Scanning

<table>
<thead>
<tr>
<th></th>
<th>Trabecular Thickness (µm)</th>
<th>Total Bone Volume Fraction (%)</th>
<th>Bone Density (g/cm²)</th>
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</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>143.6 ± 22.2</td>
<td>9.7±4.7</td>
<td>110.7±52.1</td>
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<tr>
<td>Castor Oil</td>
<td>141.3 ± 26.5</td>
<td>9.4±4.7</td>
<td>107.7±50.4</td>
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</tbody>
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Figure 1 – Repaired radius samples were subjected to either a shear/bending load (A) or pure tension (B)

Figure 2 – Failure of the adjacent bone (pink) after fixation with the castor oil based cement (white).

Figure 3 – Open pored sawbones model demonstrates enhanced penetration of cement into bone due to expansion in the polyurethane cement (left) versus an acrylic (right). Dashed black line is the fracture plane.

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