FRACTURE TOUGHNESS OF GROWTH PLATE CARTILAGE

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Introduction: The treatment and prognosis of fractures involving the physeal plate varies with the specific pattern of the fracture as described by Salter and Harris in their classification system. Little is known about the mechanical properties of the growth plate or its ability to resist tears or fractures at the microstructural level. Knowing the susceptibility of the physeal plate to fracture at the tissue level in vitro in a controlled laboratory test may help us understand the mechanisms of injury seen clinically. It may also help determine the prognosis of a given type of injury to the growth plate.

In vitro tests of growth plate microstructures have to date included tension, compression, shear and torsion tests. These are catastrophic tests in which the sample is tested to failure and the point of failure is recorded as the strength of the material. Only limited information can be obtained from such tests about the failure process itself since this occurs rapidly. The objective of this study was to determine the resistance to fracture (fracture toughness) of growth plate cartilage and to compare this to the fracture toughness of articular cartilage. We asked whether fracture toughness associated with crack propagation in the medio-lateral direction would vary with anterior to posterior location.

Methods: Fresh-frozen tibiae were obtained from two calves (Swissland Packing, Ashkum, IL) 21 weeks of age. Large blocks (25 mm x 25 mm) of bone-cartilage-bone were cut from six anatomic sites in the proximal physis with a handsaw. A diamond wafering blade was used to cut 15 mm x 15 mm blocks from within the larger block at 100 rpm. Buffered saline was used as a lubricant and all samples were kept in a protease inhibitor solution and frozen for storage. Consecutive slices were cut from the blocks resulting in samples of bone-growth plate-bone of 15 mm width and 0.4 mm thickness. A 6 mm notch was introduced into the growth plate with a #11 scalpel blade so that the tip of the notch fell within the cartilage and tended to propagate along the cartilage. With the dimensions and an average growth plate height of 0.66 mm, the region ahead of the crack tip approached a state of pure shear stress. Crack length and sample width were measured to the nearest 0.001 mm with a microscope and translating stage, and sample thickness was measured to the nearest 0.001 mm with a micrometer.

Samples were mounted in tensile grips lined with 320 grit 3M waterproof polishing paper and tested at 0.004 mm/s. Samples were observed during the test at 7 X magnification to determine the point of first visible crack propagation. The area under the load-deformation curve up to this point was calculated for each sample. The fracture toughness was obtained by dividing the resulting load-deformation area by the cross-sectional area of the portion of bone-growth plate-bone of 15 mm width and 0.4 mm thickness. A 6 mm notch was introduced into the growth plate with a #11 scalpel blade so that the tip of the notch fell within the cartilage and tended to propagate along the cartilage. With the dimensions and an average growth plate height of 0.66 mm, the region ahead of the crack tip approached a state of pure shear stress. Crack length and sample width were measured to the nearest 0.001 mm with a microscope and translating stage, and sample thickness was measured to the nearest 0.001 mm with a micrometer.

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Results: The mean growth plate thickness was 0.66 (SD 0.10) mm. We could not show that fracture toughness varied with growth plate thickness (p = 0.24). Fracture toughness ranged from 31 to 189 N/m and varied with anterior-posterior position (p < 0.001). It was largest at the most anterior and posterior sites and lowest in the middle (Table 1).

Table 1: Effect of anterior-posterior position on fracture toughness

<table>
<thead>
<tr>
<th># of tests</th>
<th>mean (SD) of fracture toughness (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>most anterior sites</td>
<td>8</td>
</tr>
<tr>
<td>more anterior sites</td>
<td>7</td>
</tr>
<tr>
<td>middle sites</td>
<td>11</td>
</tr>
<tr>
<td>more posterior sites</td>
<td>6</td>
</tr>
<tr>
<td>most posterior sites</td>
<td>6</td>
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Discussion: It has been shown that the shear strength of the proximal tibial physis in the anterior-posterior direction varies with growth plate thickness and inclination. In the present study the fracture propagation was in the medio-lateral direction, which had much less variation in inclination than the ante-ro-posterior direction. Since there is no variation in growth plate thickness in the medio-lateral direction the bi-linear variation in fracture toughness as a function of ante-ro-posterior position is likely due to variations in collagen and proteoglycans or to changes in the topography of the small mammillary processes in the frontal plane. While we were primarily interested in the energy required to make the crack propagate, we could observe qualitatively that the small mammillary processes caused the continued propagation to slow down. In some samples the fracture left a jagged fracture surface consisting of groups of entire chondrocyte columns pulled out of the opposite surface. In other samples the fracture surfaces were relatively smooth.

The fracture toughness in these ‘pure shear’ test samples of growth plate cartilage was less than that of modified single edge notch samples of articular cartilage (140-1200 N/m). This is to be expected since growth plate cartilage is more cellular than articular cartilage, except for the reserve zone, which in these samples occupied approximately 25-30% of the growth plate thickness.

It has been shown that the cartilage volume fraction in the growth plate decreases from 80% in the reserve zone to 35% in the zone of provisional calcification. In the present study the crack was cut perpendicular to the ‘grain’ of the longitudinal axis of the cartilage septa. Because of the highly anisotropic structure of the growth plate we expect the fracture toughness on a plane perpendicular to the septa, requiring the chondrocyte columns to break apart, to be greater than parallel to the septa, which requires the chondrocyte columns to be peeled apart. The jagged fracture surfaces in some samples indicated that the crack propagated perpendicular to the chondrocyte columns, then deviated along the septa in a peeling mode until it reached a weak region allowing it to break across the septa again, etc. Fracture toughness of a cellular material varies as the square of the relative density of the solid matrix. Using the fracture toughness for articular cartilage and assuming a cartilage volume fraction of at most 50% of the articular cartilage value, we would expect the fracture toughness to be 25% of the articular values. This predicts values in the range of 35-300 N/m, which compares reasonably well with the experimentally determined range of 31-189 N/m.

We conclude that there are significant regional variations in fracture toughness, which may be related to collagen or proteoglycan variations. This suggests that fracture toughness tests may provide us with a useful tool for investigating maturation and disease processes of the growth plate.

References:

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