MECHANICAL PROPERTIES OF OI TYPE III HUMAN BONE TISSUE MEASURED BY NANOINDENTATION

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Introduction: Nanoindentation was used to characterize the intrinsic mechanical properties of bone tissue from eight (8) children with type III Osteogenesis Imperfecta (OI). Unlike normal bone tissue, OI type III cortical bone exhibited more isotropic material properties. Young’s modulus and hardness values measured in the longitudinal direction did not show significant differences from the transverse measurements. No differences were observed in modulus or hardness in an analysis of the cortical and trabecular samples. The increases in isotropic and homogeneous material properties of OI bone resulted from distortions in the collagen network. Both cortical and trabecular bone demonstrated decreased mechanical properties (modulus, hardness) when compared to normal (adult) bone. These decreases were greatest in the cortical bone. The deformation patterns of the OI type III bone during nanoindentation were similar to those of normal adult bone.

Method: Eight OI type III bone specimens (aged 2.4 to 12.4 yrs.) from the lower extremities were harvested at Shriners Hospital, Chicago, during routine orthopaedic surgery (IRB approved). The tissues were freshly frozen at -20°C prior to nanoindentation testing. Before embedding, all specimens were thawed at room temperature. Then, all soft tissue was carefully dissected. Each specimen was then cut into two pieces with longitudinal and transverse surface orientation. After dehydration in air, the specimens were embedded in epoxy resin at room temperature. Silicone carbide abrasive paper (with progressively finer grit sizes of 600, 800, and 1200) was used to grind the surface of each specimen, which was then polished with a microcloth (using a 0.05 µm aluminum suspension) to produce a smooth surface for nanoindentation measurement. For each specimen, eight cortical and trabecular indents were performed in both the longitudinal and transverse directions. A Triboindenter (Hysitron, Inc. Minneapolis, MN) was used to conduct the indentation tests. The Oliver-Pharr method was used to determine the elastic modulus and hardness [1].

Results

Table 1 Young’s Modulus - Cortical Specimens.

<table>
<thead>
<tr>
<th>No</th>
<th>Anatomy location</th>
<th>Cortical bone (GPa)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Longitudinal</td>
<td>Transverse</td>
</tr>
<tr>
<td>1</td>
<td>Right radius</td>
<td>14.43 (1.65)</td>
<td>11.13 (1.90)</td>
</tr>
<tr>
<td>2</td>
<td>Left tibia</td>
<td>13.84 (1.94)</td>
<td>14.41 (2.64)</td>
</tr>
<tr>
<td>3</td>
<td>Right tibia</td>
<td>12.52 (2.33)</td>
<td>12.50 (2.13)</td>
</tr>
<tr>
<td>4</td>
<td>Left tibia</td>
<td>15.44 (2.15)</td>
<td>13.03 (2.01)</td>
</tr>
<tr>
<td>5</td>
<td>Right tibia</td>
<td>13.91 (2.16)</td>
<td>11.92 (1.33)</td>
</tr>
<tr>
<td>6</td>
<td>Right tibia</td>
<td>17.06 (2.08)</td>
<td>12.89 (1.81)</td>
</tr>
<tr>
<td>7</td>
<td>Left tibia</td>
<td>16.10 (2.95)</td>
<td>15.72 (3.00)</td>
</tr>
<tr>
<td>8</td>
<td>Right femur</td>
<td>14.7 (2.72)</td>
<td>19.76 (3.10)</td>
</tr>
</tbody>
</table>

Paired t-test (P value: 0.102)

Young’s modulus (E) measurements of cortical bone in longitudinal and transverse directions are listed in Table 1. Mean values for the series of cortical specimens were 15.22 GPa (+/- 1.94) for the longitudinal tests and 13.92 GPa (+/- 2.76) for the transverse tests. The trabecular series resulted in a mean value of 13.60 GPa (+/- 3.38). Hardness measurements averaged 0.42 GPa (+/- 0.04) for the longitudinal tests and 0.43 GPa (+/- 0.05) for the transverse tests. Trabecular specimens had an average hardness of 0.42 GPa (+/- 0.06). An unpaired t-test was performed for each specimen to explore any significant differences between longitudinal and transverse orientations at a p value of 0.05. As shown in Table 1, significant differences were observed in four of the eight specimens for Young’s modulus. To test for overall differences between longitudinal and transverse orientation, a paired t-test was performed on the average value of Young’s modulus by orientation for all eight samples. The p value was 0.102, which suggests that there is no significant difference. Using the same approach, no significant differences in hardness were observed. Trabecular modulus and hardness did not differ significantly from cortical bone.

Discussion: OI bone demonstrates abnormal collagen production and assembly, which results in an impaired collagen network with reduced collagen content, abnormal collagen arrangement, and low collagen quality. OI type III is the second most severe type of OI (Silence Classification). In OI type III patients experience frequent fractures throughout their lives, with most requiring surgical correction for repair and to reduce the risk of further fracture.

In this study, we report results from unique nanoindentation measurements of OI type III bones from human subjects. The OI type III bone was more isotropic than normal (adult) bone. The OI type III bone did not demonstrate anisotropic material properties (elastic modulus and hardness). Histomorphometric investigation reported by others suggests that there is a woven appearance and occasionally a lamellar pattern in OI type III bone tissue. Ultrastructural studies confirm a more random arrangement of collagen fibers and reduced fiber diameters [2]. The more isotropic mechanical properties of OI bone are believed to result from the abnormal collagen network. Using ultrasound critical-angle reflectometry, Mehta et al [3] found a significant decrease in the principal elastic modulus measured along the longitudinal direction of oim/oim mice bones. The modulus along the transverse direction was not reported as significantly changed. The finding is consistent with our nanoindentation results.

Compared with normal adult bone tissue, OI type III bone exhibits decreases in both modulus and hardness. These decreases are believed to be the result of OI (abnormal collagen and mineral content). They may also be at least in part due to the immature nature of the pediatric bone. The paucity of material property data for normal pediatric bone is a current challenge when attempting to differentiate the effects of disease and aging. The relative decrease in cortical bone modulus and hardness exceeds that of trabecular bone. It appears that OI may affect cortical bone properties more than those of trabecular bone. This may be due to the higher density of collagen in cortical bone and a resulting increase in sensitivity to collagen network distortion.

The E/H ratio is useful in describing material deformation during indentation. For normal adult bone the longitudinal E/H ratio is 22.50±6.14µm-1. In this study the OI type III (cortical) bone averaged a longitudinal E/H ratio of 36.2 (+/- 3.46). There was no significant difference between this OI E/H ratio and that calculated for normal adult bone (E/H = 36.7) [4]. The OI cortical bone transverse E/H ratio was similar to that of normal adult cortical bone. Pediatric bone is reported to have a higher ductility than adult bone [5]. Although there is no nanoindentation data for normal pediatric bone, it is reasonable to assume that children would have a higher modulus to hardness (E/H) ratio than adults, since the ductile materials usually have higher E/H ratio in indentation test [6]. The current study suggests that OI type III bone deforms similarly to normal adult bone. More definitive comparisons to normal pediatric bone will require additional data.

References:

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