ROLES OF TRABECULAR RODS IN DETERMINING ELASTIC MODULI OF HUMAN VERTEBRAL TRABECULAR BONE

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INTRODUCTION

Osteoporosis is an age-related disease characterized by low bone mass and architectural deterioration. Other than bone volume fraction (BV/TV), microarchitecture of trabecular bone, such as trabecular type (rods or plates), connectivity, and orientation of the trabecular bone network is also believed to be important in governing mechanical properties of trabecular bone. In a recent study [1, 2], it was found that the microarchitecture alone affects elastic moduli of trabecular bone and, further, that trabecular plates make a far greater contribution than rods to the elastic modulus of trabecular bone. In human vertebral trabecular bone, the roles of horizontal vs. vertical rods in conferring mechanical properties of trabecular bone have been debated [3, 4]. The roles of horizontal rods have been suggested to be critical in determining elastic modulus of vertebral trabecular bone. However, it is not possible yet to test this hypothesis in human trabecular bone samples despite the development of 3-dimensional (3D) micro computed tomography (μCT) and μCT based finite element models of human trabecular bone. With the newly developed 3D imaging analysis and segmentation technique of individual trabecular plates or rods [1, 2], now it is possible to examine the role of rods at individual trabecula level in elastic properties of trabecular bone. The goal of this study was to study quantitatively the relative contribution of trabecular rods in different orientations to elastic moduli of vertebral trabecular bone.

MATERIALS AND METHODS

Fourteen cylindrical human trabecular bone cores (~8 mm in diameter and 20 mm in length) in the axial direction were harvested from L4 (n=13) and L5 (n=1) vertebral bodies of fourteen donors (5 males/9 females; age 78±11). Samples were scanned at 21μm resolution using a μCT system (μCT 40, Scanco Medical Inc.). Digital topological analysis (DTA) consisting of skeletonization and classification was combined with a trabecular type-specific reconstruction technique to extract the skeleton and identify topological type of trabeculae (rods versus plates) of the original trabecular bone image [1, 2]. According to the angle θ between the macroscopic axial direction and the rod, the orientation of the rod was defined to be either vertical (0°≤θ≤30°), oblique (30°<θ≤60°), or horizontal (θ=90°) (Fig 1 and Fig 2) [2].

Table 1. Average BVF, rBV/TV, and rod # of original model and 3 reduced models.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Vertical Rod Removed</th>
<th>Oblique Rod Removed</th>
<th>Horizontal Rod Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BVF</td>
<td>0.106</td>
<td>0.104</td>
<td>0.102</td>
<td>0.102</td>
</tr>
<tr>
<td>rBV/TV</td>
<td>0.016</td>
<td>0.014</td>
<td>0.011</td>
<td>0.006</td>
</tr>
<tr>
<td>rod #</td>
<td>194.79</td>
<td>171.00</td>
<td>136.93</td>
<td>81.64</td>
</tr>
</tbody>
</table>

After removing of either the vertical, oblique or horizontal rods, all of the material constants of reduced models decreased significantly compared to the full voxel model (Fig 3). Removing horizontal rods resulted in the largest reductions in elastic moduli especially in Exx, Eyy, and Gxy. Removing vertical rods resulited in the least reduction in elastic properties, the largest being in Ezz. Oblique rods seem to contribute equally to all elastic moduli.

DISCUSSION

The roles of trabecular rods of different orientations were quantitatively studied with the newly developed morphologic analysis techniques and μCT based μFE. It has been shown for the first time that compared to vertical rods and oblique rods, removal of the horizontal rods has the greatest effect on the material constants of trabecular bone. In other studies it has been found that that the thickness of horizontal trabeculae decreases significantly with age, whereas the thickness of vertical trabeculae did not decrease significantly [4, 5]. If that were also true for trabecular rods, and considering the critical role of horizontal rods implied by the current study, the adverse effects of these processes on mechanical competence would be magnified with the decrease in the thickness of horizontal rods. It would be of significant interest in future study to examine if osteoporosis results in thinning or disconnection of rods in the horizontal direction and if pharmacological intervention can reverse this process.

ACKNOWLEDGEMENT

We would like to thank Dr. Tony M. Keaveny and Grant Bervill of Berkeley Orthopaedic Biomechanics Laboratory for providing vertebral trabecular bone images. This work was partially supported by grants from National Institutes of Health (AR049613, AR048287, AR041443, AR051376, and AR049553). REFERENCES


Fig 1. Vertical rod (left), oblique rod (middle) and horizontal rod (right) segmented from 3D μCT images of trabecular bone. θ indicates the angle between the axial direction z and the orientation of the rod.

Fig 2. Left – One of the original models, green, red, and blue represent vertical, oblique, and horizontal rods, separately, while pink represent plates. Right – the same model with all rods removed. Using an element-by-element pre-condition conjugate gradient solver, six μFE analyses were performed for each model, representing three compression tests and three shear tests, resulting a total of 336 FE analyses. The full anisotropic stiffness tensor was calculated first and elastic material constants (three Young’s moduli, Exx, Eyy, and three shear moduli, Gyz, Gzx, Gxy) were derived [3]. BV/TV, plate bone volume fraction (pBV/TV), rod bone volume fraction (rBV/TV), and rod number (rod #), were also calculated for all models. Student paired t-tests were performed between four types of models with a significant level of p<0.05.

RESULTS

Average BVF, rBV/TV, and rod # of fourteen specimens were calculated for each category of models based on a morphological analysis (Table 1). Trabecular rods accounted for 15.1% of the total BV/TV while the pBV/TV remained constant at 0.09 (84.9%) for all four models, as trabecular plates were unchanged. Horizontal rods were found to represent 62.5% of all rods in terms of bone volume, and 58.2% of all rods in terms of rod number. Vertical rods represented 12.5% of all rods in terms of bone volume, and 12.2% of all rods in terms of rod number. Oblique rods represented 31.3% of all rods in terms of bone volume, and 29.7% of all rods in terms of rod number.

Table 3. Changes of BVF, Exx, Eyy, Ezz, Gyz, Gzx and Gxy in original model and 3 reduced models.

Fig 3. Changes of BVF, Exx, Eyy, Ezz, Gyz, Gzx and Gxy in original model and 3 reduced models.