THE PROSPECTS OF ESTIMATING TRABECULAR-BONE TISSUE PROPERTIES FROM ULTRASOUND, MICRO-CT AND MICRO-FINITE ELEMENT ANALYSIS

*Van Lenthe, G.H., **Van den Bergh, J., **Hermus, A., +Huiskes, R., *+Othopaedic Research Lab, University of Nijmegen, PO Box 9101, 6500 HP Nijmegen, the Netherlands, phone: ++ 31 24 3614476, fax: ++ 31 24 3540555, email: r.huiskes@orthp.azn.nl

Introduction The mechanical quality of trabecular bone depends on the mechanical properties of the bone material itself (the tissue properties) and on its three-dimensional architecture. The architecture can be computer reconstructed with a high spatial resolution based on current micro-CT scanning. Using large-scale finite-element analysis (FEA) [1] these reconstructions can be transformed to micro-FEA models, enabling simulation of mechanical testing. In this way, the apparent elastic properties (Young's moduli) of a trabecular bone architecture can be established, given a scaling factor called the 'effective tissue modulus' (E_{tissue}). The apparent elastic properties of trabecular bone, based on architecture and tissue properties in combination, can be directly estimated from ultrasound characteristics. Both methods are, in principle, applicable in vivo, pending developments in clinical CT and MRI scanning. We hypothesize that in combining the two methods the tissue modulus can be evaluated, and used as an indicator of tissue quality. To investigate this hypothesis both methods were applied to trabecular-bone specimens.

Methods Fifteen cubes of trabecular bone (25x25x25 mm^3) were cut from eight fresh bovine femora; seven from the neck and eight from the distal part. The cubes were oriented approximately according to the anatomical axes (antero-posterior, AP; medio-lateral, ML; cranio-caudal, CC). After degassing under water, ultrasound measurements were performed along the three orthogonal axes using the clinical Ultrasound Bone Imaging Scanner 3000, DMS, France. The average velocity measured was 1860 m/s. With a frequency range of 200-600 kHz wave lengths were between 3.1 and 9.3 mm. This is much smaller than the cross-sectional dimension of the specimens, so longitudinal waves were propagated through the cubes [2]. From this longitudinal velocity (v_{long}) the bar velocity (v_{bar}) was estimated, based on the work of Njeh et al. [2], as

$$V_{bar} = 1.055 \cdot V_{long} - 1090 \quad (1)$$

The ultrasound-based apparent Young's modulus was then calculated in each direction, as

$$E_{app} = r_{app} \cdot V_{bar}^2 \quad (2)$$

where E_{app} (Pa) is the Young's modulus of the specimen, and ρ_{app} (kg/m^3) the apparent density of the specimen.

μCT scans were made of each central 6.8x6.8x6.8 mm^3 of the specimens with a resolution of 17 μm using the Scanco Medical μCT 20. These scans were converted to voxel meshes, which were coarsened by grouping 4x4x4 voxels. Each new voxel was considered bone if more than half of its original voxels represented bone tissue. From the number of bone elements the apparent density (ρ_{app}) was calculated as

$$r_{app} = r_{tissue} \cdot \frac{\#\,\text{bone voxels}}{\#\,\text{voxels}} \quad (3)$$

where ρ_{tissue} = 1739 kg/m^3 is the tissue density [3]. These models were used to determine the elastic properties of each specimen (E_{FEA}), using an arbitrary tissue modulus $E_{tissue,\ FEA}$ of 1 GPa. The effective tissue modulus was then determined as

$$E_{tissue} = E_{tissue,FEA} \cdot \sum (E_{i,app} / E_{i,FEA}) \quad (4)$$

where i = 1, 2, 3 represents the three orthogonal directions.

Results The resulting finite element models consisted of about 1.5 to $3.5*10^5$ elements. The descriptive statistics of the velocities and apparent density measured, and the apparent and tissue moduli calculated are listed in Table 1. The Young's moduli as determined from ultrasound correlated very well with the values obtained from the FEA and the calculated tissue modulus (Fig. 1).

***Table 1**: Mean values, standard deviations and ranges for ultrasound velocity, the apparent Young's modulus and the effective tissue modulus.*

	mean	SD	range
$V_{long,\ AP}$ (m/s)	1857	163	1532 - 2112
$V_{long,\ ML}$ (m/s)	1740	115	1575 - 1916
$V_{long,\ CC}$ (m/s)	1976	182	1621 - 2249
ρ_{app} (kg/m^3)	455	117	279 - 620
$E_{app,\ AP}$ (MPa)	378	191	81.5 - 659
$E_{app,\ ML}$ (MPa)	278	147	96.5 - 538
$E_{app,\ CC}$ (MPa)	500	274	113 - 991
E_{tissue} (MPa)	3733	604	2447 - 4702

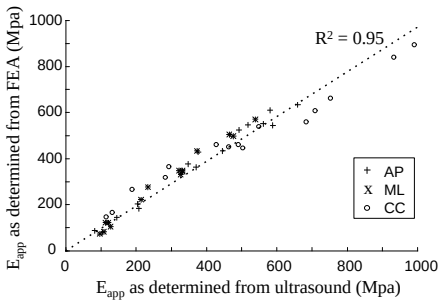

***Figure 1**: The three orthogonal Young's moduli of the bone specimens determined from ultrasound versus those determined from finite element analysis (FEA).*

Discussion The Young's modulus of trabecular-bone tissue is bound to be anisotropic and non-homogeneous, in view of its micro-morphological characteristics. It turns out, however, that these details are negligible when considering trabecular bone at the apparent level, as witnessed by the high linear correlation between micro-FEA and ultrasound determined elastic characteristics. It is remarkable that this was not disturbed by regional variation between femoral sites. Hence, characterizing the tissue with one isotropic 'effective tissue modulus' in micro-FEA seems justified.

The ultrasound-based apparent moduli were lower than the roughly 1000 MPa reported from mechanical testing of bovine specimens with similar apparent densities [2,5,6]. This can partly be caused by the presence of marrow, which has been found to decrease ultrasound velocity by about 2.5% [7]. For the velocities measured here this would indicate that the apparent modulus was underestimated by 10%. The most probable cause for this underestimation, however, might come from the proposed relationship between the longitudinal and bar velocity (eq. 1). The relationship was determined for a range of reference materials, but was not tested for trabecular bone. The effective tissue modulus determined is within the range of 0.76 to 12.7 GPa reported earlier [4]. It is somewhat less than the values of 5.3 to 7.6 GPa [8,9] found from comparing micro-FEA evaluation to laboratory testing. This may be due to the underestimation of apparent properties by ultrasound.

We conclude that although more testing of normal and osteoporotic bone is warranted, ultrasound, micro-CT and micro-FEA provide a promising combination for a determination of the 'effective tissue modulus' in trabecular bone. Potentially, bone quality could eventually be estimated clinically in this way.

References [1] Van Rietbergen et al, J.Biomech. 28, 69-81, 1995; [2] Njeh et al, Med. Eng. Phys 18, 373-381,1996; [3] Ashman and Rho, J. Biomech. 21, 177-181, 1988; [4] Rho et al., J. Biomech. 26, 111-119, 1993; [5] Ashman et al., J. Biomech. 20, 979-986, 1987; [6] Turner, J. Biomech. Eng. 111, 256-260, 1989; [7] Alves et al, Calcif. Tiss. Int. 58, 362-367, 1996; [8] Van Rietbergen et al, In: Bone structure and remodeling, 1995; [9] Ladd et al., Trans ORS 23, 112, 1998.

Acknowledgment This work was sponsored by the Dutch 'Alternatives to Animal Experiments Platform'

**Dept. of Endocrinology, University Hospital Nijmegen, the Netherlands

☐ One or more of the authors have received something of value from a commercial or other party related directly or indirectly to the subject of my presentation.

☒ The authors have not received anything of value from a commercial or other party related directly or indirectly to the subject of my presentation.