In Vivo Trabecular Bone Micro-Imaging at Isotropic Resolution Using 3D FLASE with Parallel Imaging at 3T

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Introduction: The architecture of trabecular bone (TB) has been shown to be a significant contributing factor to the bone's mechanical competence. Although noninvasive assessment of TB architecture by MRI is now feasible at locations such as the wrist and tibia [1,2], all in vivo imaging reported so far has used anisotropic resolution with a voxel anisotropy ratio of at least 3. Such anisotropy can lead to information loss when trabecular elements are small along the dimension of anisotropy. For example, in scans of the distal tibia, the lower resolution (slice) direction is typically chosen to coincide with the principal loading direction (i.e. perpendicular to the transverse plane), leading to reduced detectability of thin rod elements (~100 µm) which tend to align perpendicular to the loading direction. For quantitative analyses involving measurement of topological indices [3], this may result in artificially low rod counts and reduced sensitivity to changes in bone during longitudinal studies. A significant challenge in attaining the desired high isotropic resolution is to achieve sufficient signal-to-noise efficiency at the higher resolution. Here we have modified the FLASE pulse sequence for imaging the distal tibia at 3T with parallel imaging to achieve isotropic resolution of 160 μm^3 within a scan time of 16 minutes.

Methods: A modified 3D FLASE pulse sequence was used to acquire images of the distal tibia at 3D isotropic resolution of 160 µm3 using a 3T clinical (Siemens TIM Trio) scanner and a custom-built 4-element surface coil (Insight MRI, Worcester, MA). The field of view was approximately 8x6 cm2 with 1 cm slab thickness. Partial paral-lel imaging (reduction factor R=2 in the anterior-posterior direction) was used to acquire 64 slices in a total scan time of 16 minutes. The images were then downsam-pled in k-space to lower slice resolution (160x160x480 µm3) and the two resolutions compared, both qualitatively and quantitatively.

The pulse sequence was 3D FLASE with modifications [4] designed to improve motion correction and reduce artifacts caused by B_1 field inhomogeneity leading to an imperfect 180 degree refocusing pulse. Such artifacts are of particular concern at the higher slice resolution because the effectiveness of the crusher gradients surrounding the refocusing pulse (typically applied along the slice direction) is diminished as the imaging gradient moments increase. Therefore, special care was taken to suppress and/or move such artifacts to the edge of the field of view.

The four rectangular coil elements (approx. 5x5 cm dimensions) were arranged in a horseshoe pattern over the curved anterior surface of the ankle. Decoupling from the body transmit coil was achieved using both passive and active techniques, and preamplifier (as well as geometric) decoupling was used to avoid cross-talk between the elements. Reconstruction was performed using multi-column multi-line (MCML) GRAPPA [5] with a kernel size of 3 and 4 points in the readout and phase encode directions, respectively, and calibration region consisting of 60 phase encode lines (out of a total of 400).

Both the original and downsampled images were processed, including intensity normalization, interpolation, binarization, skeletonization, and topological classification [6]. To investigate the advantages of isotropic resolution, the resulting 3D cores were compared qualitatively, and topological parameters were also compared between the higher and lower slice resolutions.

Results and Discussion: A single axial slice of an isotropic data set is shown in Figure 1 along with the 3D processed skeleton and extracted cores oriented transversely and longitudinally. The intricate structure of the trabecular bone network is clearly resolved, and the preferential orientation of plates (i.e. along the loading direction) is evident. The topological classifications are illustrated in Figure 2 (plates in white, plate edges in red, and rods in blue), for both the isotropic and downsampled images. The 3D rendered image confirms that small perforations in plates and thin rod elements oriented transverse to the loading direction can only be detected at the higher resolution, previously only possible ex vivo by micro-CT.

A comparison of structural parameters between the higher and lower slice resolution data sets is given in Table 1. While bone-volume fraction (BV/TV) and skeleton density are relatively close, the topological parameters, particularly surface-to-curve ratio, are significantly different between the two slice thicknesses. The data are consistent with the illustration of Figure 2, in that plate counts (surfaces) are increased while rod counts (curves) are decreased at the anisotropic resolution. The data again suggest that perforations in plates as well as the presence of rods oriented perpendicular to the loading direction (both biomechanically relevant) are detected more accurately at isotropic resolution. The voxel volume used of 4.1×10^{-3} mm^3 is a factor of 2-5 smaller than what has previously been possible clinically at peripheral sites [1,2,7].

	160x160x160 resolution	*160x160x480 resolution*
Bone-volume fraction	11.7%	11.2%
Skeleton density	8.1%	8.4%
Surface density	6.5%	7.4%
Curve density	0.83%	0.51%
Junction density	0.69%	0.56%
Surface/Curve Ratio	7.8	14.7

Table 1: Comparison of structural parameters between high (isotropic) and lower (anisotropic) resolution.

Conclusion: The data are the first to demonstrate the feasibility of imaging trabecular bone *in vivo* at isotropic resolution providing detailed insight into the plate-rod architecture of the trabecular network in all three dimensions.

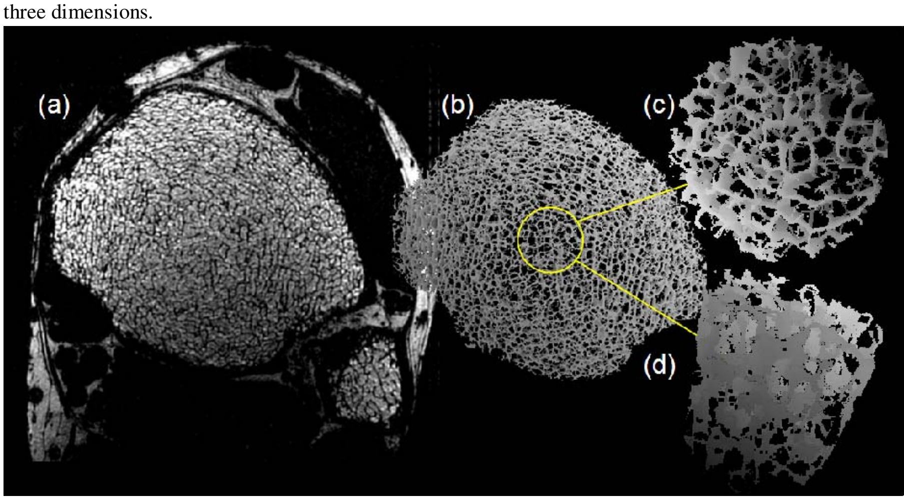

Figure 1: (a) Axial image of tibia acquired at 160 micrometer isotropic voxel size. (b) 3D TB skeleton obtained from (a) with magnifactions at (c) axial and (d) coronal orientations. The 3D structure is accurately depicted, with plates oriented primarily along the longitudinal (loading) direction, and connecting rods oriented transversely.

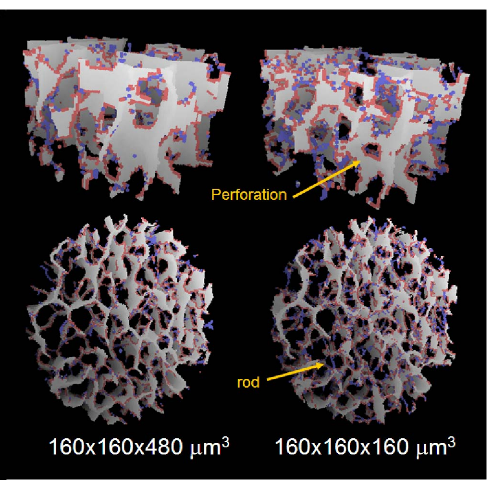

Figure 2: 3D TB skeleton cores colored by topological classifications at low and high slice resolution. Features such as perforations and rods can only be seen at the higher slice resolution.

References: [1] Benito et al, J Bone Min Res, 20(10), 2005; [2] Chesnut et al, J Bone Miner Res, 20(9), 2005; [3] Wehrli et al, J Bone Miner Res, 16(8), 2001; [4] Magland et al, ISMRM 2007, #382; [5] Wang et al, MRM 54, 2005; [6] Gomberg et al, IEEE TMI, 19, 2000; [7] Boutry et al, Radiology, 227(3), 2003.

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