Feasibility of high resolution partial parallel imaging in the distal tibia for improved structural anisotropy analysis

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Introduction: Structural anisotropy, a measurement of trabecular bone's (TB) orientational dependence, is a useful metric for monitoring the mechanical adaptation of the skeleton during aging and disease. Quantification of TB structural anisotropy is difficult in the limited resolution and signal-to-noise ratio (SNR) of *in vivo* micro-MRI. The examination of TB structure requires voxel sizes on the order of its thickness (~100μm) and sufficient volume along the longitudinal axis of the bone where marrow spacing is maximal (600-3000 μm) to accurately capture material fabric. To improve the volume coverage without significantly increasing scan time, partial parallel imaging (PPI) (R=2) using a four-element phased array (PA) ankle coil and the 3D fast large angle spin echo (3D FLASE) [1] pulse sequence was investigated *in vitro*. Partial parallel acquisitions were simulated and reconstructed using a 2D GRAPPA technique with multi-column multi-line interpolation (MCMLI) and the structural anisotropy was computed using the spatial autocorrelation function (ACF) for both R=1 and R=2 datasets.

Materials and Methods: A 4-element receive-only PA coil, shown in Fig.1, was built for high resolution imaging of the distal tibia. Each element is a 4x3.5cm^2 rectangle of 0.5cm thick cooper tape, tuned to 123.26 MHz, matched to a 50 ohm load, and decoupled from the body coil via a current blocking loop consisting of an inductor and diode. Element dimensions were chosen to achieve optimal SNR at the center of the ankle with the ankle modeled as a cylinder [2]. Inter-element coupling was reduced by a single stage capacitive ladder network [3]. Each coil was attached to the receiver via a λ/2 transmission line (coaxial cable of λ/4 and custom-built eight channel low-input impedance preamplifier). Inter-element decoupling was measured via scattering parameters to be better than -24dB between all elements when connected to preamplifier.

A cadaveric tibia specimen (67 year old female) fixed in 10% formalin solution was positioned in the center of the coil to prevent significant signal shading from any individual element. Two datasets were acquired consecutively using the 3D FLASE (TE/TR/BW=10.5/80/33 ms/ms/kHz) pulse sequence on a Siemens Trio Scanner without disturbing the specimen: 1) 137x137x410 (μm)^3 voxel size and 13mm slab in 15 min; 2) 137x137x410 (μm)^3 voxel size and 26mm slab in 30 min. 2D PPI (R=2) along the PE direction was simulated by removing PE lines and a GRAPPA based reconstruction using MCMLI [4] was optimized by minimizing the relative root of mean squared distance (RRMS) between the pair of images I_{ref} and I_{recon} where the size of the interpolation net [Nc,Nl] (Nc is # of k_x pts, Nl is # of k_y pts) and the number of auto-calibration lines (ACL) were varied. The parameters that minimized the RRMS with respect to scan time were then used to down-sample and reconstruct the 3D datasets.

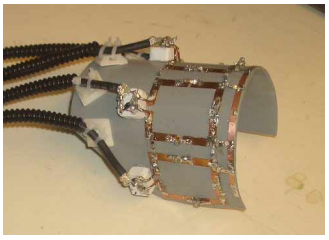

Fig 1. Capacitively decoupled four-element PA ankle coil.

The 3D datasets were manually masked, bone-volume-fraction mapped [5], and subvoxel processed [6] prior to structural anisotropy analysis via the ACF algorithm [7]. By sampling the 3D ACF in spherical coordinates and approximating TB thickness as the full-width at half maximum and TB separation as the distance between the primary and secondary maxima of the ACF, the orientational dependence was mapped and fit to an ellipsoid. The structural anisotropy is computed as the ratio of the largest (e_1) to smallest eigenvalues (e_3) of the ellipsoid and the preferential direction is noted by the angle (θ_z) between the eigenvector associated with e_1 and the bone's longitudinal axis.

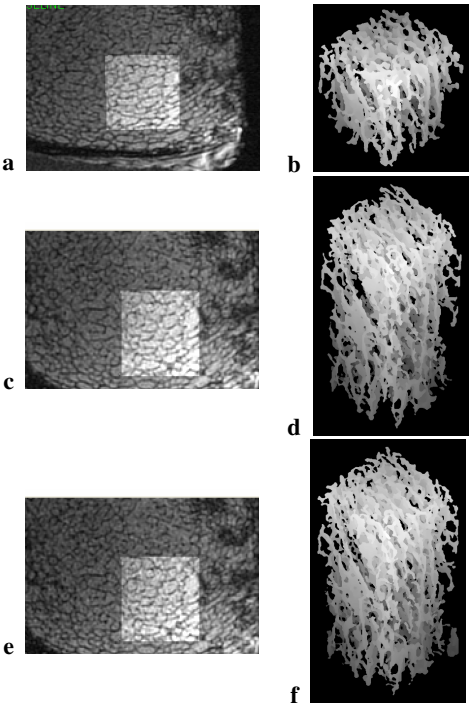

Fig 2. a),c),e) Slices from full-FOV 13 mm slab dataset, full-FOV 26mm dataset, and 26mm (R=2) reconstructed dataset. Location of parallelepiped subvolumes shown in b), d), and f) are highlighted. Left to right corresponds to the lateral to medial direction. Subvolumes are from approximately the same anatomical location and are rotated counterclockwise by 45° relative to images a),c), and e).

Results: The optimized 2D PPI reconstruction parameters were determined for a 3D FLASE acquisition: Nc=3; Nl=7; ACL=20, which results in a 8:21 min (R=2) 137x137x410 (μm)^3 13mm slab acquisition and 16:40 min (R=2) 137x137x410 (μm)^3 26mm slab acquisition. Slices from the full-FOV and R=2 dataset along with parallelepiped subvolumes from approximately the same anatomical location within the distal tibia are shown in Fig 2.

Structural anisotropy data are summarized in Fig 3. The TB separation ellipsoids illustrate the local in plane orientation seen in Fig 2a-e that is characteristic of TB close to the cortex. Fig 3.a illustrates the advantage of increased volume coverage. The TB separation in the transverse plane is different by less than 3% between the 13 mm and 26 mm slabs, while the TB separation along the bone's longitudinal axis, e_1, is smaller by 21% in the 26 mm slab. The reduction in e_1 is due to the better sampling of the marrow spacing, which results in better resolved secondary maxima in the ACF along the bone's longitudinal direction. Similarly, lower structural anisotropy is measured in the scan with increased coverage along the longitudinal axis, e_1/e_3=5.43 (13 mm) vs. e_1/e_3=3.89 (26 mm).

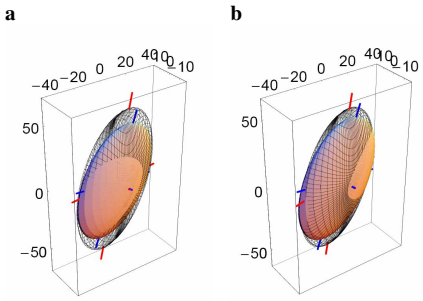

Fig 3. Comparison of anisotropy ellipsoids for: a) TB separation in 13mm (mesh surface and red eigenvectors) and 26 mm (solid and blue eigenvectors) slab acquisitions; b) TB separation in 26 mm, R=1 (solid, blue) & 26 mm, R=2 (mesh, red) acquisitions. Left to right in box corresponds to the lateral-medial direction.

The two-fold acceleration also affects the measured structural anisotropy and preferential direction of TB separation: e_1/e_3=3.89 (4.54) and θ_z=18.2 (8.1°) for R=1 (2), as shown in Fig 3.b. The longitudinal separation e_1 is 14% larger in the R=2 dataset while the transverse separation changes by less than 1%. This difference suggests that accelerated acquisitions may significantly alter the measured structural anisotropy, albeit to a lesser extent than insufficient volume coverage.

Conclusions: PPI in micro-MRI using the 3D FLASE sequence provides larger through plane coverage in a clinically feasible scan time. The additional volume is valuable for the examination of TB structural anisotropy since it allows better sampling of the marrow spacing.

References: **1**.J. Ma et al., *Magn Reson Med* 35, 903 (Jun, 1996). **2**.J. Wang et al., *IEEE Trans Biomed Eng* 42, 908 (Sep, 1995). **3**.J. Jevtic, ISMRM 2001. **4**. Z. Wang et al., *Magn Reson Med* (Oct 24, 2006). **5**.B. Vasilic et al., *IEEE Trans Med Imaging* 24, 1574 (Dec, 2005). **6**.S. Hwang et al., *Magn Reson Med* 47, 948 (May, 2002). **7**.M. Wald et al., SPIE Medical Imaging, San Diego, CA 2005.

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