Imaging of Trabecular Bone Architecture at Isotropic Resolution by a New Variable-Echo Hybrid Radial Acquisition Technique

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Introduction

Next to bone volume fraction, the architecture of trabecular bone (TB) significantly determines the bone's mechanical competence [1]. Noninvasive assessment of TB architecture by MRI at selected anatomic locations such as the wrist [2] or tibia [3] at a resolution sufficient to at least partially resolve individual trabeculae is now feasible. However, all imaging in vivo reported so far used anisotropic resolution with a voxel anisotropy ratio of at least 3, thus causing significant partial volume mixing and causing errors in the retrieval of the 3D structure of the TB network. Here, we present a new hybrid radial pulse sequence which allows structural imaging of TB at the wrist or tibia at a voxel size of 156x156x156 μm^3 in a scan time of 14 minutes.

Methods

The pulse sequence, optimized for high-resolution *in vivo* imaging of trabecular bone at peripheral skeletal locations, is shown in **Figure 1**. It consists of a selective RF pulse and uses sampling of a cylindrical k-space volume by means of radial readouts in two directions and phase encoding in the third (slab-select) direction. At TR=26 ms, 500 views are collected in each of 64 phase encoding steps within a total scan time of 14 minutes. Sampling 180° around the circle yields a reconstruction matrix size of approximately 320x320x64 ($320 \approx 500 / (\pi/2)$) with no PR aliasing. For a field of view of 5x5x1cm, this produced the desired 156 µm isotropic voxel size. The flip angle chosen was 30° to select a 1 cm slab. Another feature of the pulse sequence is a variable echo time of 2.5 ms for the lowest spatial frequencies k_z, 4.0 ms for intermediate, and 6.0 ms for the highest k_z values. The data were reconstructed by 3D FFT after regridding the data onto a uniform Cartesian grid. A deconvolution technique was used to correct for chemical shifts due to off-resonant frequencies in the spectrum of the bone marrow and to eliminate any artifacts caused by the varying echo time (see [4]). Finally, the data was multiplied by a Hanning window to reduce the noise coming from the high-frequency data, and the reconstructed image was processed using an iterative algorithm to de-noise the homogeneous regions. The performance of the pulse sequence for the intended purpose is illustrated with the 1.5 T images (Siemens Sonata) of an intact specimen of the human distal tibia, fixed in 10% formalin (**Figures 2** and **3**). The data were obtained with a currently used clinical birdcage coil for imaging the distal radius and thus suggest that in vivo measurements at this site are feasible in clinically tolerable scan times.

The purpose of varying the echo time was to capture the highest possible signal at the center of k-space in order to achieve a signal-to-noise ratio (SNR) comparable to that of the FLASE sequence [5]. Using steady-state SNR formulas, we predict that for an ideal effective echo time of 0 ms, a 40% gain in SNR could be achieved over FLASE for the same scan time and voxel volume (assuming T1=300 ms and T2=40 ms for bone marrow). The mathematical derivation of this SNR prediction is beyond the scope of the abstract. Of course, the present effective echo time is somewhat longer, so the actual SNR gain will be less than 40% and further depends on T_2* of the bone marrow signal.

Besides the SNR gain, the main advantage of the hybrid radial technique over FLASE is the short repetition time of 26 ms which allows acquisition of up to twice as many slices as FLASE in the same scan time. Unlike FLASE, which is sensitive to RF inhomogeneity of the refocusing pulse [6], the new micro-imaging pulse sequence is free of artifacts and allows for improved motion correction [7], and has decreased overall SAR.

Results

Figure 2 shows a single slice in the reconstructed image clearly delineating trabecular structure at this resolution with high contrast-to-noise. **Figure 3** shows longitudinal reformations at two different slice thicknesses (156 µm and 400 µm), illustrating the advantage of the higher resolution in depicting the trabeculae oriented perpendicular to the principal loading direction. We noticed no artifacts in the reconstruction due to the variable echo time.

We expect significant SNR improvements in future work by imaging at a higher field (3T) and by shortening the echo time using ramp sampling or a half pulse excitation.

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References

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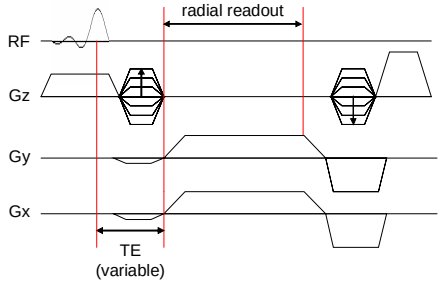

Figure 1. Variable echo-time hybrid radial sequence.

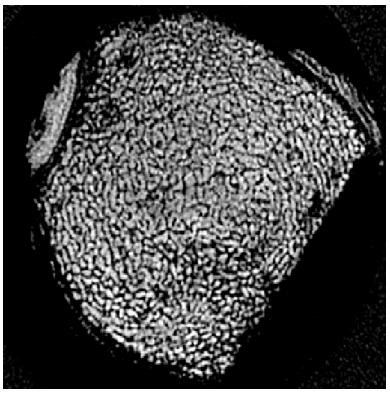

Figure 2. A single slice of thickness=156 µm

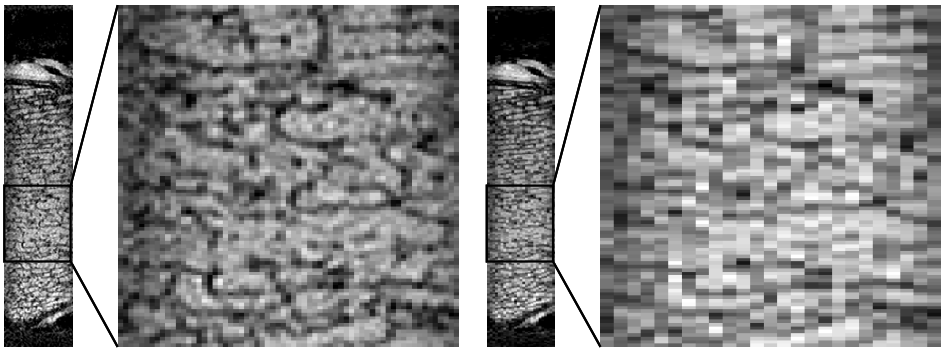

Figure 3. Longitudinal reformations (left) slice thickness = 156 µm. (right) slice thickness = 400 µm.