Quantification of bone-water concentration in a 3T whole-body imager using solid-state imaging

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Background and Motivation

Cortical bone contains approximately fifteen percent water by volume [1]. Some of the water is bound to collagen but most resides in the microscopic pores of the lacuno-canalicular system. With advancing age bone porosity increases along with a reduction in the bone's mechanical competence [2]. Since the pores range in diameter from sub-µm to tens of µm, porosity is not amenable to measurement *in vivo* by direct observation. However, it is possible to image bone-water (BW, T_2=200-500 µs depending on field strength [3]) using solid-state imaging (SSI) techniques. Here we advance the hypothesis that we can quantify BW and thus potentially pore volume *in situ*.

Materials and Methods

We used as a model cortical bone from the tibial mid shaft of adult sheep. The H_2O fraction was controlled by graded exchange through immersion of the bone in H_2O/D_2O mixtures of varying isotopic ratio which simulate varying BW content as resulting from variations in bone porosity. Prior to imaging the bone was cleaned of soft tissue and marrow, cut transversely into two 2.5cm-long specimens and immersed in the mixture. Once exchange equilibrium is attained, the isotopic ratio in the bone and the surrounding mixture should be equal. Based on preliminary experiments, the bone was immersed in H_2O/D_2O mixtures for a period of at least 36 hours at 55 ºC (to enhance the exchange rate) to reach the exchange equilibrium.

The pulse sequence (Fig. 1) employs a half-rf pulse for excitation in combination with center-out radial sampling to capture the center portion of *k*-space as early as technically possible. Duration between the peak of the excitation and the start of the acquisition (often referred to as *echo time* (TE) although no real echo is formed) here is limited by the rephasing lobe of the slice-select gradient because data sampling begins during the ramp-up period of the readout gradients. Half-pulses require combination of pairs of views collected with opposite polarity of the slice-select gradient [4]. Subsequently, the combined data were regridded and reconstructed with standard 2D FT.

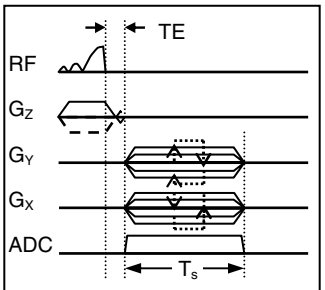

Fig. 1. SSI sequence with half-*sinc* excitation and radial readout. The dashed line shows the two opposite polarities of the slice-select gradient. The sequence also employs read-gradient rewinders (not shown) to rephase the spins at the end of sequence cycle.

The imaging experiments were performed on a 3.0 Tesla Siemens Trio system using a 6.5cm x 5.5 cm transmit/receive birdcage coil. The bone specimens were removed from the mixtures, blotted dry and placed in a closed glass vial to be scanned along with a reference sample. The half-rf pulse used was a half-*sinc* pulse with 2 side lobes and total duration of 0.6 ms. The imaging parameters were as follows: TE=0.13ms, TR=500ms, voxel size = 0.5x0.5x10 mm^3, flip angle = 90º, readout bandwidth = 560 Hz/pixel. 1607 views were acquired over 2π for a total scan time of 27 min.

By comparing the signal intensity relative to the reference, the BW concentration was computed as $(I_{bone}/I_{ref})c_{ref}$ where c_{ref} is the H_2O concentration of the reference sample after correction for T_1, T_2^* and B_1 inhomogeneity. The B_1 correction was achieved from the ratio of two-double-angle spin-echo images as described in Reference 5. T_1 and T_2^* of bone were measured from projection images, using the same pulse sequence. The reference sample was prepared from a 33.33% (by volume) H_2O/D_2O mixture doped with 3 mM Gd-DTPA to shorten its T_1 and T_2 value to ~80ms.

Results and Conclusion

Fig. 2 shows cross-sectional cortical bone images at 5 different H_2O concentrations. BW concentration obtained by SSI is plotted as a function of H_2O concentration in the H_2O/D_2O isotopic mixtures (Fig. 3). BW SNR ranged from ~45 in its native state (100% H_2O) to ~3.5 after complete exchange (nominally 0% H_2O). T_1 and T_2^* at 100% H_2O were 248±12 ms and 480±22 µs, respectively. The high linearity and goodness of the fit (r^2=0.995, p=0.0001 in specimen A and r^2=0.994, p=0.0002 in specimen B) suggest that high measurement precision is achievable. BW concentration was found to be ~16% and 17% by volume for specimens A and B, respectively, in good agreement with the literature [1]. The non-zero BW signal intensities after full exchange as also observed in [6] are likely to arise from nonexchangeable water or non-water proton resonances. Reproducibility of the technique was measured by scanning bone at its native state three times yielding a coefficient of variation of 5.30% and 2.95% in specimens A and B, respectively. The data show that BW content and thus potentially porosity can be measured with high precision. Extension to *in vivo* measurements in humans appears feasible, at least at the tibia, in conjunction with soft-tissue suppression techniques [7, 8].

Fig. 2. 3T axial proton images of sheep tibia (mid shaft, with ~3-4mm cortical thickness) obtained after exchange in isotopic mixtures of H_2O/D_2O. SNR ranges from ~3.5 at 0% (bone is barely visible at this window/level) to ~45 at 100%. Scan time was 27 min and voxel size was 0.5x0.5x10 mm^3.

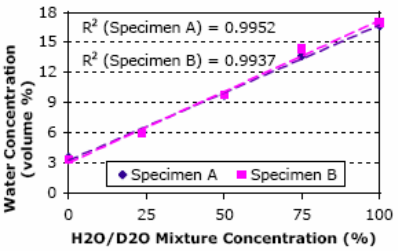

Fig. 3. Bone-water concentration quantified by solid-state imaging.

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