Quantification of bone-water concentration in the human tibia in vivo by 3T solid-state radial imaging

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Background and Motivation

With advancing age bone porosity increases along with a reduction in the bone's mechanical competence [1]. 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) which mostly resides in these microscopic pores of the lacuno-canalicular system. This pore water has extremely short T_2 and thus exhibitis solid-like behavior with a linewidth on the order of 1kHz therefore requiring solid-state imaging (SSI) techniques. Here we demonstrate the feasibility of quantifying BW and thus potentially pore volume *in vivo* in the cortex of the human tibia.

Materials and Methods

A SSI pulse sequence was designed using the Siemens IDEA pulse sequence editor allowing for both 2D and 3D imaging. The 2D sequence employs a 560 μs total duration truncated two-sidelobe half-*sinc* pulse [2] terminated at its peak with the variable-rate selective excitation (VERSE) principle [3] applied during slice-select gradient down-ramp to allow both events to end simultaneously thus eliminating the need for gradient rephasing. The signals from the two excitations with opposed slice-select gradient polarity were combined with real components adding and undesired imaginary components canceling. The 3D sequence employs a 100 μs rectangular pulse with radial encoding in-plane and phase-encoding in z direction. To reduce the duration between the peak of the excitation and the start of data acquisition (often referred to as echo time, TE, even though no real echo is formed) the z-phase encoding gradient was designed for maximum strength and slew rate at each encoding step thus resulting in minimum TE (equal to the receiver dead time) for the k_z=0 line and gradually increasing toward k_z^{max} line [4]. Both sequences used radial readout with ramp sampling. The radial data were regridded and reconstructed with standard FT.

In vivo images were obtained in the right tibial midshaft of three healthy volunteers using an eight-element transmit/receive knee coil array. The imaging parameters were FOV=300mm^2, slice thickness=8mm, receiver bandwidth=700Hz/pixel, TR/flip angle=300ms/65º (2D) and 70ms/41º (3D) and twenty-three of the 256 samples were collected during the 140μs ramping period. For 2D sequence, TE=0.05ms. For the variable-TE 3D sequence TE_{min}=0.09ms, TE_{max}=0.23ms. The 2D images were acquired in the single slice mode with 800 views over 360º in an 8 min scan time. The 3D images were acquired with 256 views over 360º for 30 slice encodings in a 9 min scan time. For better visualization of bone, additional soft-tissue signal suppressed images were acquired with two 5ms rectangular T_2-selective (TELEX [5]) pre-pulses applied at the frequencies of water and fat protons followed by spoiler gradients. For water quantification an external reference signal prepared from 20% (by volume) H_2O/D_2O mixture doped with 137mM $CuSO_4$ to shorten its T_1 and T_2 to 11 and 7.5 ms was attached next to the skin. All experiments were performed on a 3T Siemens Trio™ system.

$$\frac{\rho_{bone}}{\rho_{ref}} = \frac{I_{bone}/f \cdot (1-e^{-TR/T_{1,ref}}) \cdot (1-\cos\alpha \cdot e^{-TR/T_{1,bone}})\, e^{-TE/T_{1,ref}}}{I_{ref} \cdot (1-e^{-TR/T_{1,bone}}) \cdot (1-\cos\alpha \cdot e^{-TR/T_{1,ref}})\, e^{-TE/T_{2,bone}}} \qquad \text{Eq.1}$$

BW concentrations can be computed by comparing the signal intensity of bone relative to that of the reference after correction for T_1, T_2* and flip angle. In addition, when the inequality $\tau_{RF} << T_2$ (where τ_{RF} = duration of the RF pulse) is not satisfied, there is non-negligible transverse magnetization decay during the application of the pulse as well as residual longitudinal magnetization resulting from incomplete nutation of the spins. Thus, the effective transverse magnetization has to be accounted for quantification. The effective transverse magnetization due to the loss during excitation were calculated from Bloch equation simulations for the half-pulses and the rectangular pulses to be 80% and 92%, respectively, of its nominal value at the TR and flip angle used. BW was computed using Eq.1 where $f = M_{eff}/M_{nominal}$ with $M_{nominal}$ being the transverse magnetization under conditions where $\tau_{RF} << T_2$ applies.

Results and Conclusion

Table 1. Cortical BW concentrations calculated from *in vivo* SSI images of the tibial midshaft with an aid of a reference phantom.

Sequence	Subject 1	Subject 2	Subject 3
2D	19.2%	24.3%	21.1%
3D	18.0%	22.4%	19.2%

Fig. 1 shows transverse *in vivo* images in one subject. BW concentrations calculated from the non-suppressed SSI images of three subjects obtained with both 2D and 3D sequences are given in Table 1. The values found are in good agreement with the literature of ~20% (by volume) [6]. Reproducibility was estimated in one of the subjects by repeating the scans three times on different days. The coefficients of variation were 7.6% and 6.4% for the 2D and 3D SSI sequences, respectively. The data show that BW and thus potentially porosity can be measured in vivo of humans.

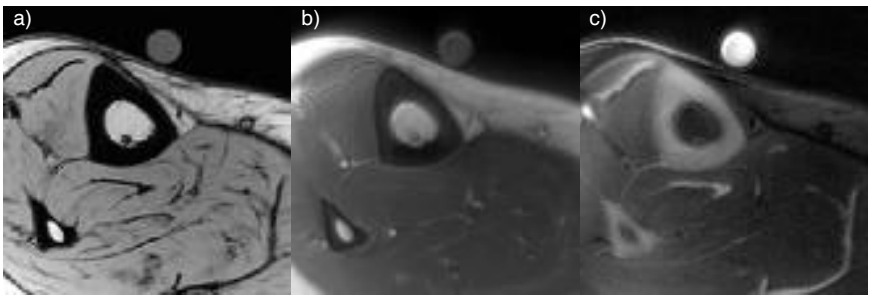

Fig. 1. *In vivo* images of the tibial midshaft: a) gradient-echo; b,c) 2D SSI without and with soft-tissue suppression. Soft-tissue suppressed image (c) highlights the water proton signal in cortical bone (T_2*<1ms) with SNR~35 obtained in ~8mins scan time at 0.58x0.58x8 mm^3 voxel size.

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