Implications of soft-tissue suppression on cortical bone water signal in ultrashort echo-time imaging

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Introduction Cortical bone water, present both as collagen-bound water and as free-water within the Haversian canals and lacuno-canalicular system, is characterized by extremely short T2 times, and is difficult to visualize on images acquired with conventional echo times. Ultrashort echo-time (UTE) imaging allows for detection of the rapidly decaying cortical bone water signal [1,2]. However, the presence of strong signals from water in the surrounding muscle and fat in the subcutaneous tissue and marrow hinder visualization of the bone water signal. Furthermore, the marrow signal complicates segmentation of the endosteal boundary when calculating bone water concentrations. Soft-tissue suppression has been utilized to minimize the long-T2 water and fat signals [3]. While soft-tissue suppression enhances cortical bone visualization, it unavoidably suppresses a fraction of the cortical bone water signal. Importantly, suppression of the bone water signal may not be uniform throughout the cortex given that cortical bone pore size increases from the periosteum to the endosteum. This gradation in pore size is augmented with aging as a result of endosteal resorption [4,5]. T2 of the water in larger pores is likely lengthened due to the reduction in surface interactions as the surface-area/volume ratio decreases [6,7]. Soft-tissue suppression may, therefore, suppress the bone water signal of larger pores to a greater degree than that of the smaller pores. Here, we employ *in vivo* UTE imaging of the mid-tibia both with and without soft-tissue suppression to determine the degree of bone water suppression within different regions of the cortex. We hypothesize that suppression of bone water will vary with both the location in the cortex and the age of the subject.

Methods ***MR image acquisition:*** The mid-tibia (38% site as measured from the lateral malleolus) of six healthy volunteers [3 young (ages 26-27) and 3 elderly (ages 74-78)] was imaged with a 3D hybrid-radial ultrashort echo time (3D HRUTE) sequence [8] both with and without soft-tissue suppression on a Siemens 3T Tim Trio scanner using an 8-channel Tx-Rx knee coil. A hyperbolic secant (HS) adiabatic inversion pulse was used to suppress both long-T2 water and fat [2]. To minimize bone water suppression and maximally suppress the long T2 species, the HS pulse was optimized as follows: 1) Bandwidth/pulse duration = 1kHz/20ms, with a frequency shift of 250Hz towards the lipid peak in order to cover both fat and water peaks; 2) The frequency was swept from water to fat, inverting water before fat to compensate the T1 difference between the two entities; 3) The HS pulse amplitude was set to allow 30% B1 variation. Scan parameters for UTE without suppression were as follows: FOV=180×180×40mm^3, 500 radial projections, 256 readout samples, 4 slices, reconstructed pixel size=0.38×0.38mm^2, TR/ TE_{min} /flip angle=300ms/80µs/60˚. The imaging parameters were identical for UTE with suppression except TI = 100ms. Reference samples of 20% H_2O in D_2O doped with 27 mM $MnCl_2$ yielding T2*~320µsec were placed on the anterior surface of the tibia to ensure consistent suppression of short-T2 species among scans.

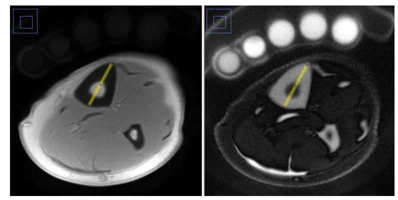

Figure 1. Non-suppressed (A.) and soft-tissue suppressed (B.) UTE images of the mid-tibia from a 27 y.o. subject. Straight profiles extend across the anteroposterior surface of the tibia.

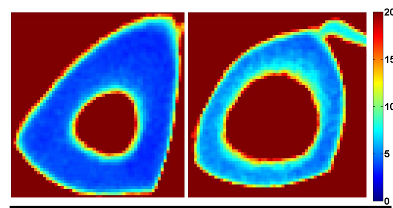

Figure 2. Suppression ratio color maps from 27 y.o (A.) and 78 y.o (B.) subjects highlight the varying degrees of cortical bone water suppression.

Image analysis: A straight profile (5 pixels thick) was drawn across the tibia from the anterior to the posterior surface on a single slice of the non-suppressed UTE image (**Figure 1**). The profile was then replicated in the soft-tissue suppressed image. The signal intensity of the pixels highlighted by the two lines was plotted as a function of the percentage of cross-sectional length (each point being an average of 5 pixels). The intensity values from the non-suppressed image were divided by the values from the soft-tissue suppressed image at each profile location, yielding a graph of the suppression ratios as a function of the cross-sectional length. Pixel suppression ratios, displayed as color maps (MatLab 7.0), were calculated by dividing the signal intensity of each pixel in a single slice of the non-suppressed UTE image by the signal intensity of the corresponding pixel in the soft-tissue suppressed UTE image. An automated segmentation algorithm was used to segment the endosteal and periosteal boundaries on the non-suppressed UTE images [9]. This segmentation was then applied to the suppression ratio color maps. The mean and standard deviation of the suppression ratios of the pixels in the newly segmented region was computed for each subject. The values were then compared between the two age groups (unpaired Student's *t*-test).

Results The adiabatic inversion pulse achieved excellent suppression of soft tissue (**Figure 1B**). The suppression of the reference samples was consistent between scans (1.59±0.07). Suppression of the bone water signal varied with both subject age and with location in the cortex. Suppression ratio-based color maps (**Figure 2**) demonstrated uniform suppression throughout the cortical bone in the young subjects, while variable levels of suppression were apparent in the elderly group. These observations made from the color map images were supported by a trend toward higher standard deviations of pixel suppression ratios within the cortical bone in the elderly group compared to the young group (2.05±1.16 vs. 0.91±0.36, p=0.179). There was also a trend toward a higher mean pixel suppression ratio in the elderly group (6.32±1.66 vs. 3.96±0.38, p=0.075). The plot of suppression ratios along the anteroposterior axis of the tibia (**Figure 3**) demonstrates an increase in bone water suppression from the periosteum to the endosteum in older individuals, which is also apparent on the color maps **(Figure 2)**. The increase in the suppression ratio from the periosteum to the endosteum likely correlates with an increase in pore size and a lengthening of the T2 of the water in the larger pores. The trend toward a higher mean value of the suppression ratios in the elderly group may reflect increased cortical bone porosity in these subjects. Irrespective of the cause, the variation of the suppression ratios is problematic when attempting to calculate bone water concentration. Preferential suppression of the endosteal pore water is particularly troubling, as this is the area where pore size is known to increase the most with aging.

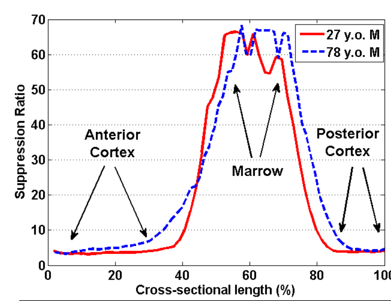

Figure 3. Plots of cortical bone water suppression ratios along the anteroposterior axis of the mid-tibia in a young (red) and an elderly subject (blue).

Conclusion Long-T2 water and fat suppression with an adiabatic inversion pulse results in high levels of soft-tissue suppression. The undesired suppression of cortical bone water varies with location in the cortex and appears to be age-dependent, potentially confounding measures of bone water concentration. The correlation between the level of bone water suppression and T2 values in the larger pores needs to be further elucidated. If there is indeed a correlation, bone water suppression ratios may provide indirect estimates of porosity.

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