Can we assess cortical bone microstructure with magnetic resonance imaging?

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INTRODUCTION

Cortical bone is a composite material containing approximately 20% water by volume. Bone water occurs at various locations and in different binding states, including water bound to organic matrix and free water residing in the microscopic pores of cortical bone [1]. Cortical bone is typically regarded as "MR invisible" with conventional clinical MR sequences [2-4]. However, recent studies have demonstrated that free water in pores has a long T2 of 100 ms or longer, and may be detectable with conventional clinical FSE sequences [5]. Both bound and free water may be detected with ultrashort echo time (UTE) sequences with a minimal nominal TE of 8 us [6-8]. In this study, we aimed to investigate bone water imaging with UTE and clinical FSE sequences, and to correlate the structure seen with FSE imaging with that seen with μCT imaging.

MATERIALS AND METHODS

Fifteen human tibial midshatft samples were harvested from cadaveric leg specimens. The human cortical bone samples were cleared of external muscle and soft tissue. Bone marrow was removed with a scalpel. Cross-sectional human cortical bone segments with a thickness of 20-30 mm were prepared for 2D and 3D UTE sequences to image both bound and free water. 2D and 3D adiabatic inversion recovery prepared UTE (IR-UTE) sequences were used to image bound water. Clinical 2D FSE sequences were used to image free water in cortical bone on a 3T GE whole-body scanner. Each bone sample was placed in a 30 ml syringe filled with fomblin during MR imaging to maintain hydration and minimize susceptibility effects at air-bone junctions. Typical imaging parameters included: FOV = 4 cm, slice thickness = 5 mm for 2D UTE and 0.5 mm for FSE, reconstruction matrix = 512×512, TR = 300 ms for UTE and 3000 ms for FSE, TI=120 ms for IR-UTE, bandwidth = 62.5 kHz, TE = 8 μs for UTE and 15 ms for FSE. The effect of TR, echo train length (ETL) and averaging were investigated for 2D FSE imaging. A home-built birdcage coil (~2.5 cm in diameter) was used for signal excitation and reception. After MRI, each bone sample was subject to μCT imaging on a Skyscan 1076 (Kontich, Belgium) scanner with a resolution of 47×47×47 μm^3. Cortical porosity derived from FSE images and μCT images were compared. Finally, a translational 2D UTE and clinical 2D FSE imaging protocol was used for imaging the tibial mid-shaft of six healthy volunteers with a home-build receive-only surface coil (~2.5 cm in diameter) used for signal reception.

RESULTS and DISCUSSION

Figure 1 shows the results of 2D FSE, 2D GRE, 2D and 3D UTE, as well as 2D and 3D SIR-UTE imaging of a cortical bone sample. Free water in the Haversian canals is well depicted by the 2D FSE sequence, but appears as a signal void with the 2D GRE sequence, consistent with free water in cortical bone having a long T2 but short T2*. The 2D and 3D UTE sequences detected both free water in the pores which appeared as high signal fine structure, as well as water bound to the organic matrix which appeared as uniform background signal. The high signal fine structure disappeared with the 2D and 3D SIR-UTE sequence where the free water signal was suppressed by the adiabatic IR preparation pulse. The uniform background signal was probably from water bound to the organic matrix.

Figure 2 shows selected 2D FSE imaging and μCT imaging of cortical bone samples. There is a high morphological correlation between these two imaging techniques, suggesting that 2D FSE imaging is able to detect cortical pore structure.

Figure 3 shows the correlation between porosity assessed by μCT imaging and porosity assessed by 2D FSE MR imaging. There is a high correlation between these two imaging modalities (R2 = 0.8287; P < 0.0001), suggesting that clinical 2D FSE imaging can reliably assess cortical porosity.

Figure 4 shows conventional FSE, UTE and IR-UTE imaging of the mid-shaft of the tibia in volunteers with a 1-inch surface coil. This allows high spatial resolution FSE images to be obtained with voxel sizes of 78×78×700 μm^3, with adequate SNR in a scan time of 6.5 minutes. High quality UTE and IR-UTE images are also obtained.

Studies by Bell et al have shown that giant canals with diameters > 385 μm make a substantial contribution to cortical porosity, and have a negative influence on the ability of cortical bone to withstand stresses associated with a fall (93). Therefore, direct imaging of such giant canals with 2D FSE sequence combined with technical approaches including relatively low resolution, thick axial slices and high performance local coils may make it possible to evaluate bone quality in vivo using clinical MR sequences.

CONCLUSIONS

The long T2 bone water components can be assessed with clinical 2D FSE sequences. Both short and long T2 bone water components can be assessed with 2D and 3D UTE sequences. Clinical gradient echo sequences provide little signal from cortical bone probably due to the short T2* from both bound and free bone water components relative to the minimum achievable TE with these sequences.

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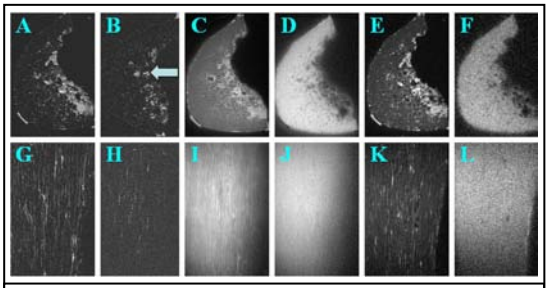

Fig 1 *Axial (1st row) and sagittal (2nd row) imaging of a human cortical bone sample with 2D FSE (A, G), 2D GRE (B, H), 2D UTE (C, I), 2D IR-UTE (D, J), 3D UTE (E, K) and 3D IR-UTE (F, L) sequences. Free water in the Haversian canals is detected by FSE, 2D and 3D UTE sequences. 2D and 3D IR-UTE images show a relatively uniform bright signal, consistent with only bound water being detected. The GRE images show little signal from cortical bone. The bright signal in GRE images corresponds to marrow fat (B, arrow).*

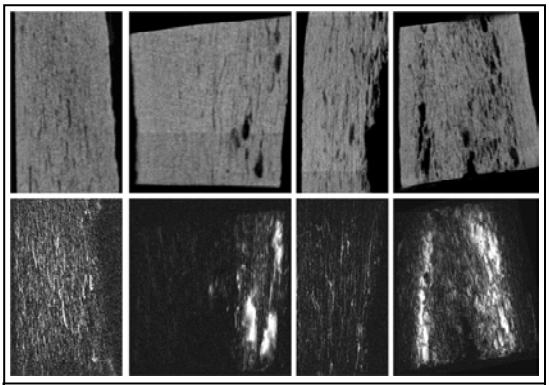

Fig 2 *μCT (1st row) and FSE (2nd row) imaging of four human cortical bone samples. There is a high morphological correlation between these two imaging modalities.*

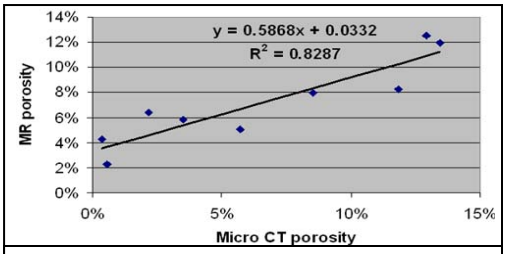

Fig 3 *Correlation between FSE MRI and μCT porosity.*

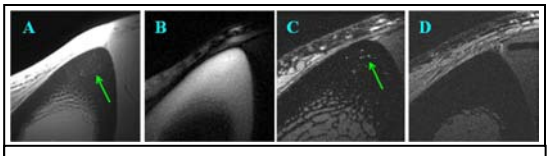

Fig 4 *Axial imaging of the tibia mid-shaft of a 58 y volunteer with UTE (A), IR-UTE (B) and FSE (C) sequences, and FSE imaging of a 39 y volunteer (D). UTE detects signal from both bound and free water (A). IR-UTE shows water bound to the organic matrix (B). The fine structures in FSE images correspond to the large Haversian canals (C). The younger volunteer shows no structure in cortical bone with the FSE sequence, consistent with bone without larger canals (D).*