High-Resolution 3D Fast Spin-Echo MRI Combining Variable Refocusing Flip Angles with Outer Volume Suppression at 3T

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Introduction: High-resolution imaging of the central body regions is usually hampered by long scan time in order to acquire the complete data without aliasing. One important application of high-resolution MRI is imaging trabecular bone structure in the context of osteoporosis in vivo [1]. Proximal femur fractures are the most severe complication of osteoporosis, leading to high rates of mortality and morbidity, but structural analysis of the proximal femur has been limited due to its deep-seated location. Recently, 3D balanced steady-state precession (bSSFP) has shown great feasibility of delineating the microstructure at the proximal femur by virtue of its high SNR efficiency [2]; however, bSSFP often suffers from signal loss due to field inhomogeneities and chemical shift. Here, we propose a new high-resolution imaging technique for assessing bone structure in the proximal femur by combining variable flip-angle 3D fast spin-echo sequence and outer volume suppression [3] at 3T.

Methods: A commercial version of a variable flip-angle 3D FSE sequence (CUBE) was modified to incorporate outer volume suppression (OVS-CUBE) to limit the phase-encode FOV and avoid aliasing at a MR750 3T scanner (GE Healthcare, Waukesha, WI). For outer volume suppression, three quadratic-phase RF pulses [4] with flip angles of 90°, 90°, and 116° (bandwidth: 8 kHz for 90° pulse and 6.8 kHz for 116° pulse) were applied on one region at optimized time points for the suppression to be insensitive to B_1 and T_1 variation [5] (Fig. 1). For acquisition, ten echoes were acquired per echo train using centric ordering, and the flip angles of nonselective refocusing pulses were calculated using the extended phase graph algorithm given the minimum and central flip angles of 90° and maximum flip angle of 120° [6] (Fig 2). This flip angle optimization aimed to minimize blurring without decreasing SNR much.

Ex-vivo experiments were conducted using a proximal femoral head specimen from a female patient with osteoporotic fracture using an eight-channel phased-array knee coil (InVivo Corporation, Gainesville, FL). CUBE acquisition was performed without outer volume suppression, employing a 10 x 10 cm^2 FOV, 512 x 512 matrix size (195 x 195 um^2 in-plane resolution), 44 sections with 0.5 mm thickness, and 8.8 ms echo spacing. In addition, high-resolution peripheral quantitative CT (HR-pQCT) imaging, with which accuracy for trabecular structure measurement was validated [7], was performed on a XtremeCT (Scanco Medical, Brüttisellen, Switzerland) with an isotropic voxel size of 41 um. For in-vivo study, coronal hip imaging was conducted for six healthy volunteers using an eight-channel phased-array cardiac coil (GE Healthcare, Waukesha, WI). Both our OVS-CUBE and two phase-cycled bSSFP images were acquired using the imaging parameters of a 12 x 12 cm^2 FOV, 512 x 512 matrix size (234 x 234 um^2 resolution), 64 sections with 0.6 mm section thickness. With OVS-CUBE, one sagittal saturation slab was placed on the other side of the body to prevent aliasing artifacts from that region. For bSSFP, other scan parameters included 60° flip angle, 8.6 ms TR, 3.1 ms TE (fractional echo), and the phase-encode direction (superior/inferior direction) was oversampled by a factor of two to avoid aliasing artifacts. Scan times were 21 mins for OVS-CUBE and 11 mins for bSSFP.

Results: Figure 3 shows slices on identical position of the specimen from HR-pQCT and MR images after automatic registration using the software TRI/3D-Bon (Ratoc System Engineering Co., Tokyo, Japan). Trabecular bone structures from CUBE images are qualitatively similar to those from HR-pQCT demonstrating that CUBE with optimized refocusing flip angles could be appropriate to reliably assess bone structure. An in-vivo study from one volunteer is illustrated in Fig 4. The new imaging sequence depicts trabecular bone structure without visible aliasing artifacts and provides more homogenous bone marrow signal than bSSFP. With bSSFP, bone marrow signal is low in the femoral neck and intertrochanteric regions owing to the presence of hematopoietic marrow (40% lipid, 40% water), and trabecular structure appears to be thicker caused by susceptibility differences at bone-marrow interfaces.

Discussion: We have shown that a new high-resolution OVS-CUBE sequence has great potential to accurately assess small structures in the central body regions without visible aliasing artifacts. The robustness to chemical shift by using the spin-echo type sequence is highly advantageous in structural analysis of the proximal femur, where bone marrow can be spectrally heterogeneous with abundant hematopoietic marrow. Currently, outer volume suppression is only applied to one side of the body, but suppression of the left and right sides of the FOV might be necessary to further improve resolution. One limitation of using OVS-CUBE for proximal femur trabecular bone imaging is the relatively long acquisition time; however, ongoing developments including advanced phased-array coils will further improve SNR, enabling acceleration using parallel imaging or partial Fourier.

References

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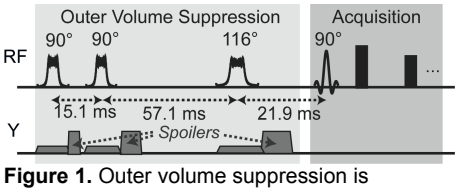

Figure 1. Outer volume suppression is incorporated prior to fast spin-echo acquisition to reduce the phase-encode FOV.

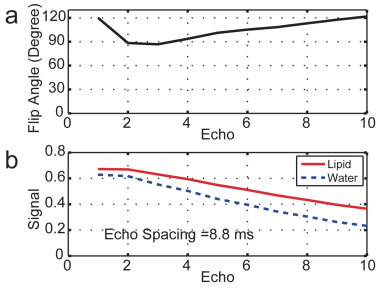

Figure 2. (a) Refocusing flip angle variation for an echo train. (b) Estimated echo signal variation from bone marrow (simulation with T_1/T_2= 300/80 ms for lipid component and 1200/50 ms for water component).

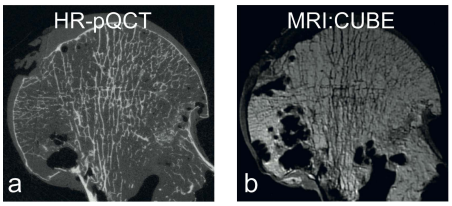

Figure 3. Ex-vivo images from HR-pQCT (a) and MRI with CUBE (b). Bone structures from both images are qualitatively similar. Different appearances of air inclusions are a result of different scan dates.

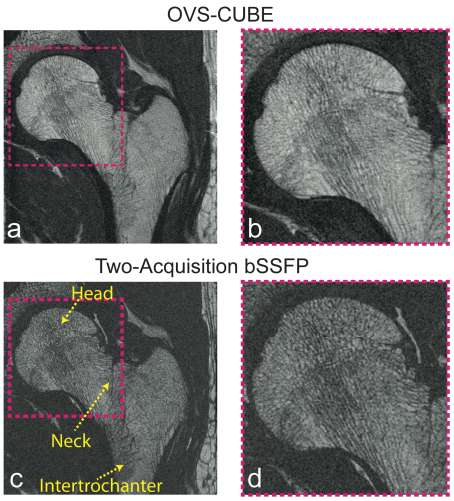

Figure 4. In-vivo proximal femur images with OVS-CUBE (a) and bSSFP sequences (c). The zoomed images of the square boxes are shown in (b,d). With OVS-CUBE, trabecular bone structure is well-depicted without aliasing artifacts.