Three-dimensional adiabatic inversion recovery prepared ultrashort echo time cones (3D IR-UTE-Cones) imaging of cortical bone in the hip

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Abstract
Purpose: We present three-dimensional adiabatic inversion recovery prepared ultrashort echo time Cones (3D IR-UTE-Cones) imaging of cortical bone in the hip of healthy volunteers using a clinical 3T scanner.
Methods: A 3D IR-UTE-Cones sequence, based on a short pulse excitation followed by a 3D Cones trajectory, with a nominal TE of 32 μs, was employed for high contrast morphological imaging of cortical bone in the hip of healthy volunteers. Signals from soft tissues such as muscle and marrow fat were suppressed via adiabatic inversion and signal nulling. T2 value of the cortical bone was also calculated based on 3D IR-UTE-Cones acquisitions with a series of TEs ranging from 0.032 to 0.8 ms. A total of four healthy volunteers were recruited for this study. Average T2 values and the standard deviation for four regions of interests (ROIs) at the greater trochanter, the femoral neck, the femoral head and the lesser trochanter were calculated.
Results: The 3D IR-UTE-Cones sequence provided efficient suppression of soft tissues with excellent image contrast for cortical bone visualization in all volunteer hips. Exponential single component decay was observed for all ROIs, with averaged T2 values ranging from 0.33 to 0.45 ms, largely consistent with previously reported T2 values of cortical bone in the tibial midshaft.
Conclusions: The 3D IR-UTE-Cones sequence allows in vivo volumetric imaging and quantitative T2 measurement of cortical bone in the hip using a clinical 3T scanner.
structure of interest, however, there are no commercially available coils for dedicated hip imaging. In addition, to create high contrast images, cortical bone signal must be preserved while undesired components are suppressed. This includes fat in the marrow and extramedullary locations as well as surrounding long T2 structures such as muscle.

In this study, we report the use of three-dimensional adiabatic inversion recovery prepared UTE with Cones sampling (3D IR-UTE-Cones) to directly image and quantify cortical bone in the hip in vivo at 3 T.

2. Methods

2.1. Pulse sequence

The 3D UTE-Cones sequence is shown in Fig. 1A. The 3D UTE-Cones sequence employs a hard RF pulse for non-selective excitation, and center-out 3D spiral trajectories for k-space sampling [26], as shown in Fig. 1B. It also employs short readout times, which in combination with the centric trajectory, allows for signal acquisition from the rapidly decaying tissue components. The 3D UTE-Cones sequence is more time-efficient than radial trajectories in covering 3D k-space [26]. Also, the 3D UTE-Cones sequence resolves the sensitivity of the 2D UTE sequences to eddy currents by employing a hard RF pulse instead of a half RF pulse for signal excitation. Moreover, the 3D UTE-Cones sequence allows for anisotropic fields of view (FOVs) and spatial resolution (higher in-plane resolution with thicker slices), resulting in vastly reduced scan times. By using the 3D UTE-Cones sequence, 3D volumetric UTE imaging can be obtained in an SNR efficient way.

When followed by an adiabatic inversion recovery preparation pulse, the 3D UTE-Cones sequence can be utilized to acquire signal from cortical bone with high contrast [27,28]. This is done by inverting the longitudinal magnetization of the long T2 signal components (i.e., muscle and bone marrow fat) while saturating the signal from cortical bone [27–31]. The Cones acquisition starts after an inversion time (TI) delay, which is used to null the long T2 components while permitting detection of recovered cortical bone signal (Fig. 1C).

2.2. T2 measurement with 3D IR-UTE-Cones

The steady-state 3D IR-UTE-Cones signal can be calculated as follows:

\[
M_{ir}^{xy}(T1, TE) = M_0 e^{-\frac{T2}{T2}} + \text{noise},
\]

Eq. (1) describes that T2 of cortical bone can be measured by mono exponential fitting of the acquired IR-UTE images at different TEs. It should be noted that TR/TI combination should be able to null the signal from the long T2 components in the bone marrow and muscle.

2.3. MRI protocol

The 3D IR-UTE-Cones sequence was implemented on a 3 T scanner (Signa HDx, GE Healthcare, Milwaukee, WI) [27]. The sequence has a minimal TE of 32 μs and allows anisotropic field of view and spatial resolution for fast volumetric imaging. An adiabatic inversion pulse (duration = 8.64 ms) was used for robust inversion and suppression of the longitudinal magnetizations of long T2 water and fat. Four healthy volunteers (28, 31, 34, and 43 years old, male) were scanned by using a torso phased-array coil. The following scan parameters were used: TR = 116.7 ms, TI = 50 ms, four TEs (0.032, 0.2, 0.4, and 0.8 ms), BW = 250 kHz, FOV = 340 × 340 mm², slice thickness = 3 mm, matrix = 128 × 128, flip angle = 18°, acquired voxel size = 2.6 × 2.6 × 3 mm³, and scan time = 4.5 min for each dataset. T2 was quantified with a single-component decay fitting of the multi-echo 3D IR-UTE-Cones images.

2.4. Data analysis

The code for the analysis was written in MATLAB (The MathWorks, Massachusetts) and was executed on the DICOM images obtained by the aforementioned protocols in the experimental setup section. The program allowed for the delineation of regions of interest (ROIs) on

Fig. 1. The 3D UTE-Cones sequence employs a short rectangular pulse for signal excitation, followed by a 3D Cones trajectory (B) to allow time-efficient sampling with a minimal TE of 32 μs. The 3D UTE-Cones sequence combined with an adiabatic inversion recovery preparation pulse (3D IR-UTE-Cones) can invert and null the signal from long T2 components, including fat and muscle, allowing the cortical bone to be selectively imaged (C). In (C), the dashed curve line and the red solid line represent the long T2 components and the short T2 components, respectively. The dotted line illustrates that after time TI the signal from the long T2 components is nulled (reaching zero) while a significant amount of signal from the short T2 components remains.

Fig. 2. (A) The 3D IR-UTE-Cones sequence provides excellent image contrast for cortical bone in the hip obtained with TR = 116.7 ms, TI = 50 ms and TE = 0.032 ms for a healthy volunteer (34-year-old man); (B) Four representative ROIs are defined for T2 analysis, including the greater trochanter (ROI1), the lateral aspect of the femoral neck (ROI2), the femoral head (ROI3), and the lesser trochanter (ROI4). The approximate locations of the selected ROIs are shown in the figure with different colors.
the UTE images. Four ROIs were drawn in the proximal femur for T2⁎ analysis. As shown in Fig. 2, ROIs included the greater trochanter (ROI1), the lateral aspect of the femoral neck (ROI2), the femoral head (ROI3), and the lesser trochanter (ROI4). The average intensity of voxels within the ROIs was used for subsequent curve fitting. In addition, T2⁎ of the cortical bone were calculated using Eq. (1).

3. Results

Fig. 2 shows a representative image of the hip of a 34-year-old healthy volunteer imaged with the 3D IR-UTE-Cones sequence. Cortical bone in the greater trochanter, the femoral neck, and the femoral head, as well as lesser trochanter is depicted with excellent image contrast. Muscle and marrow fat about the hip, which typically have far higher signal than that of cortical bone, were efficiently suppressed by the adiabatic inversion pulse. SNR for cortical bone in the femoral head is relatively low due to the thin structure and limited coil sensitivity from the clinical torso phased array coil.

Cortical bone in the hip at four different TEs of 0.032, 0.2, 0.4 and 0.8 ms is shown in Fig. 3. As can be seen, excellent contrast can be achieved by using the 3D IR-UTE-Cones sequence with rapid decay of signal. Fig. 4 shows representative signal decay curves for the greater trochanter, the femoral neck, the femoral head, and the lesser trochanter in a 34-year-old male volunteer. Excellent single-component exponential decay was observed for all the ROIs, with a short T2⁎ of 0.41 ± 0.11 ms for the greater trochanter, 0.33 ± 0.08 ms for the femoral neck, 0.34 ± 0.05 ms for the femoral head, and 0.33 ± 0.04 ms for the lesser trochanter.

Table 1 summarizes the mean and standard deviation for T2⁎ values for the greater trochanter, the femoral neck, the femoral head, and the lesser trochanter, respectively, between the four volunteers. The average T2⁎ values ranged from 0.33 to 0.45 ms, and were largely consistent with previously reported T2⁎ values of bound water in the tibial midshaft.

4. Discussion

In this study, a direct MR-based imaging technique, based on IR-UTE technique, for cortical bone in the hip was reported for the first time in vivo. Although direct imaging of cortical bone has previously been presented at different locations such as the midshaft of the tibia [28,32–34], direct imaging of the hip is considered of higher clinical significance since fractures at this location are more devastating [3]. In addition, imaging at this location is considered more technically challenging.

Preliminary results from this study have shown that the cortical bone in the hip can be imaged using the 3D IR-UTE-Cones sequence (Fig. 3). The adiabatic inversion pulse provides robust suppression of
Table 1

<table>
<thead>
<tr>
<th>Cortical bone in different sites of the hip</th>
<th>Greater trochanter</th>
<th>Femoral neck</th>
<th>Femoral head</th>
<th>Lesser trochanter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_2^* ) in ms (mean ± std)</td>
<td>0.40 ± 0.05</td>
<td>0.38 ± 0.04</td>
<td>0.37 ± 0.04</td>
<td>0.38 ± 0.03</td>
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Conflicts of interest
None.

References


