In vivo conductivity imaging of human knee using 3 mA injection current in MREIT

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Abstract. Recent in vivo human leg MREIT experiments showed successful conductivity image reconstructions using carbon-hydrogel electrodes and optimized RF coils. However, it is still difficult to perform in vivo human and disease model animal experiments primarily due to a long scan time and high injection current of about 9 mA. Compared to previous MREIT pulse sequences, a newly developed multi-echo pulse sequence provides a higher SNR of MR magnitude image and better quality of magnetic flux density data. Unlike the human calf, the knee has sensitive nerve bundles and mainly consists of the bone. In this study, we tried to obtain high-resolution conductivity images of in vivo human knees using the multi-echo pulse sequence. We injected as much as 3 mA current in the form of an 81 ms pulse into the knee without producing a painful sensation and motion artifacts. Reconstructed conductivity images well distinguish different parts of the subcutaneous adipose tissue, muscle, synovial capsule, cartilage and bone inside the knee. Considering clinical applications, future work should be focused on in vivo human and disease model animal experiments.

Keywords: MREIT, conductivity image, human knee

1. Introduction

Magnetic resonance electrical impedance tomography (MREIT) has been recently proposed for cross-sectional conductivity image reconstructions with a spatial resolution of a few millimetres [1-4]. Incorporating a constant current source to an existing MRI scanner, the MREIT technique is expected to provide new contrast information. Postmortem and in vivo animal imaging studies demonstrated that we can produce high-resolution conductivity images of intact animals [5-7]. Though the first trial of human imaging experiments has been lately reported [8], this new imaging method requires further human studies focusing on organs of interest in terms of their conductivity values.

In MREIT, it is still difficult to perform in vivo human and disease model animal experiments primarily due to a long scan time and high injection current of about 9 mA. Compared to previous MREIT pulse sequences, a newly developed multi-echo pulse sequence provides a higher SNR of MR magnitude image and better quality of magnetic flux density data [9]. Since the knee has sensitive nerve bundles, we tried to reduce the current amplitude by adopting this new pulse sequence. The purpose of this study is to show the potential of the MREIT technique as a new clinically useful imaging modality through human imaging experiments. Describing the imaging method, we will show cross-sectional conductivity images of the human knee.
2. Methods

2.1. Normal volunteers

Four healthy volunteers (2 males, 2 females, 25 to 32 years old) participated in the human experiments. All human experiments were performed following the protocol approved by the Institutional Review Board (IRB). After attaching four electrodes around the knee, we chose one pair of electrodes to inject current. Starting from zero mA, we gradually increased the amplitude of the injection current pulse. The subject’s oral response was recorded to mark the current amplitudes for the thresholds of sensation and pain. The same procedure was repeated for the other pair of electrodes. The amplitude of imaging current was determined as the 90% of the smaller pain threshold.

2.2. Imaging experiment

We attached four carbon-hydrogel electrodes around the knee to inject currents (figure 1). We injected 3 mA currents in two mutually perpendicular directions using two pairs of electrodes. Subjects were examined on a 3.0 Tesla MRI scanner (Magnum3, Medinus, Korea) with a 22 cm STR coil. Imaging parameters using multi-echo (3 echos) spin echo pulse sequence were as follows: TR/TE = 900/30 ms, flip angle = 70°, FOV = 220×220 mm², slice thickness = 6 mm, NEX = 12, matrix size = 128×128, number of slices = 8 and total imaging time = 100 min.

![Figure 1](a) Carbon-hydrogel electrodes and (b) electrode attachment around the human knee.

2.3. Conductivity image reconstruction

We used CoReHA (conductivity reconstructor using harmonic algorithms), which is an integrated software package for MREIT [10,11]. It provides GUI-based functions for all data processing routines needed to produce conductivity images from measured k-space data sets. We used the single-step harmonic Bz algorithm implemented in CoReHA for multi-slice conductivity image reconstructions [12]. All conductivity images presented in this paper should be interpreted as equivalent isotropic scaled conductivity images providing only conductivity-based contrast information. Interpretation of these images should be pursued in future work.

3. Results

The mean threshold current by the subject’s oral response was 3.5 ± 0.2 mA. We injected as much as 3 mA current in the form of an 81 ms pulse into the knee. Figure 2(a) is a MR magnitude image of the knee from the normal male subject. Figure 2(b) and (c) show Bz images in the same imaging slice subject to the horizontal and vertical current injections, respectively. Figure 3 compares the anatomy of the knee in (a) with an MR magnitude image in (b) and a reconstructed conductivity image in (c). Conductivity images of the knee well distinguished different parts of the subcutaneous adipose tissue,
muscle, synovial capsule, cartilage and bone inside the knee.

Figure 4 shows the anatomy of the knee in (a) with an MR magnitude image in (b) and a reconstructed conductivity image in (c) from the normal female subject. In (b), we can see that MR signal void occurred at the outside of the bones. The conductivity image in (c) exhibits spurious noise spikes there. We observed no significant conductivity difference between male and female subjects.

The semi-automatic boundary extraction method implemented in CoReHA often resulted in somewhat distorted shape of the outermost boundary in conductivity images. This minor geometrical distortion has negligible effects in reconstructed conductivity images since the harmonic $B_z$ algorithm is insensitive to geometrical errors.

![Figure 2](image1.jpg)

**Figure 2.** (a) MR magnitude image of the knee from the male subject. (b) and (c) are magnetic flux density images subject to the horizontal and vertical injection currents, respectively, using 3 mA imaging currents.

![Figure 3](image2.jpg)

**Figure 3.** (a) Anatomy of the male knee. (b) and (c) are MR magnitude and reconstructed conductivity images, respectively.

![Figure 4](image3.jpg)

**Figure 4.** (a) Anatomy of the female knee. (b) and (c) are MR magnitude and reconstructed conductivity images, respectively.
4. Discussion

Numerous previous MREIT experiments of postmortem and \textit{in vivo} animals enabled us to design the human experiment and successfully produce \textit{in vivo} conductivity images of the human knee with a pixel size of about 1.7 mm. Though the first trial of human imaging experiments has been lately reported, it is still difficult to perform \textit{in vivo} human and disease model animal experiments primarily due to a long scan time and high injection current. In this paper, we could reduce the current amplitude to 3 mA by using a multi-echo pulse sequence. We expect that the multi-echo pulse sequence is advantageous for further \textit{in vivo} conductivity imaging of human subjects using 3 mA or less imaging currents. We plan to perform numerous \textit{in vivo} animal and human experiments to advance the MREIT technique to the stage of clinical uses.

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