Investigation of RF penetration in humans at ultrahigh magnetic fields

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Introduction: The phased array [1] is able to improve Signal to Noise Ratio (SNR) and support parallel acquisition [2,3] and parallel transmission [4,5] to accelerate imaging speed. The coil penetration which describes the available SNR at a depth is an important issue in array coil designs. The coil penetration is not only determined by the coil itself, but also related to the electromagnetic properties and geometry of imaging samples. Different human tissues/body parts have different permittivity (ε) and conductivity (σ) and different shapes, therefore the RF field distribution of the same coil varies in different tissues or body parts [6,7]. In this work, analysis of the RF field distributions of surface coil was investigated for human liver and brain imaging at 7T using Finite-Difference Time-Domain (FDTD) method with a high fidelity human whole-body model (Remcom Inc. State College, PA). Different penetration performance of the same coil in the two human tissues is observed.

Theory and Methods: The human liver has an irregular shape with relatively high conductivity, leading to the conductivity-effect-dominated B_1 distribution [6]. Therefore the liver acts as an RF shield impeding the penetration of the RF fields into the liver. This can be described by the skin depth:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (1)$$, where ω, μ, σ denote the angular frequency, permeability and conductivity respectively.

From this equation it is shown that the RF penetration inside a tissue is inversely proportional to the tissue conductivity and the resonant frequency. In the human liver, the conductivity is relatively large and the shape is irregular. At low fields, the skin depth phenomenon is not obvious because the frequency is low; however, at ultrahigh fields, when the resonant frequency increases to 300 MHz or higher, the conductivity effect becomes dominant and decreases the penetration of the RF field. This is very different from human brain imaging where the conductivity is small, permittivity is large and the shape is comparatively regular. Tissues or body parts with high permittivity and regular geometric shape attempt to "resonate", especially at high frequency, which helps improving RF field penetration [7]. To analyze these differences, FDTD method was utilized to evaluate the field distributions of a surface coil loaded with high fidelity human whole body model (Remcom Inc. State College, PA).The surface coil was modeled as a copper loop with 8 cm O.D. and 7 cm I.D. The selection of the coil size for the calculation model was based on our imaging experience at 7T. Surface coils with 8-cm diameter or less resonating at 300MHz can be realized using a conventional approach without a significant design effort. In the human liver simulation, this coil model was placed above the liver and was approximately 1 cm away from the abdomen, as shown in Fig.1a and c. In the human brain simulation, this coil model was positioned behind the occipital lobe and was approximately 1 cm away from the head, as shown in Fig.1b and d. A current source was utilized to feed the coil and generate a 300 MHz RF field. The stop criteria for FDTD calculation is convergence to -40 dB. Both B_1+ and B_1- field distributions were simulated for axial and sagittal planes. The MR signals were calculated using the following equation [8]:

$$I \propto \sum_{N} \left| W_n \sin\left(V \left| B_{1n}^{+} \right| \gamma\tau\right) \left(B_{1n}^{-}\right)^{*} \right| \quad (2)$$, where N is the total number of the voxels within the field of view; B_{1n}+ and B_{1n}- denote the transmission field and reception field respectively; γ denotes the gyromagnetic ratio. V is a normalization factor which is used to achieve the maximum signal at the nearest position to the coil within the human body.

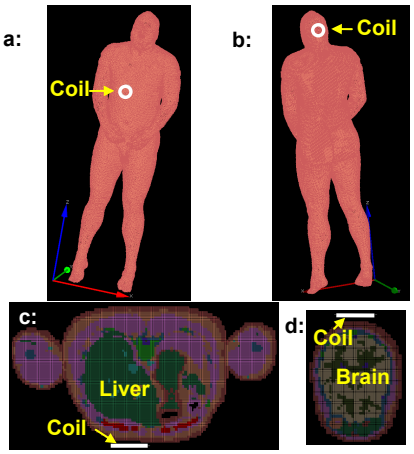

Fig. 1 FDTD setup for penetration comparison between human liver and brain: (a, b) 3D view of coil setup for human liver and brain; (c, d) 2D views of the setup for liver and brain.

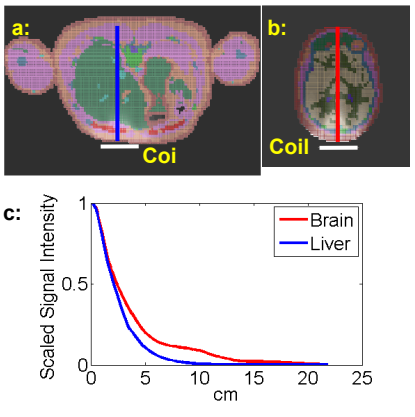

Fig. 2 Axial images of (a) the liver and (b) the brain. (c) 1D profiles demonstrate the RF penetration of corresponding liver and brain images using the same coil.

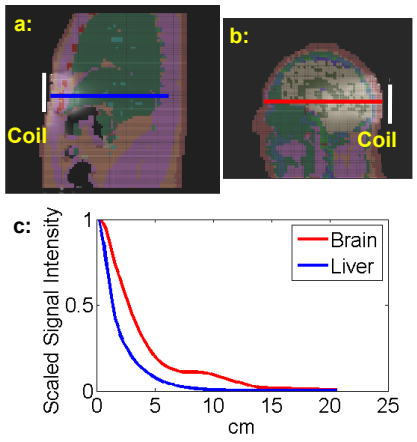

Fig. 3 Sagittal images of (a) the liver and (b) the brain. (c) Corresponding 1D plots show the penetration difference between liver and brain using the same coil.

Results: Fig.2a and b show the signal intensity of the axial planes of the liver and brain respectively. Fig.2c is their corresponding 1D profile of the signal intensity along the blue and red solid lines indicated in Fig.2a and b. At 10 cm away from the coil surface, the signal intensity decreases to 8.8% in the brain while decreases to 0.7% in the liver. It is clearly demonstrated that using the same surface coil, the B_1 penetration was fairly different in different imaging objects. In the liver, the conductivity is high and its shape is irregular, therefore the conductivity effect impedes the field penetration. In the brain, the permittivity is much higher than that of the liver and the brain's shape is comparatively regular, consequently dielectric resonance effect helps the improvement of the B_1 field penetration into the brain. These conductivity effects and dielectric resonance effects become much more obvious with the increase of field strength. Fig.3 shows the 2D views and 1D plots of the liver and brain signal intensity in the sagittal plane. It is shown that at 10 cm away from the coil surface, the signal intensity decreases to 9.4% in the brain and to 0.7% in liver. The obvious penetration difference again demonstrated that different body tissues have different effects on RF field penetration.

Conclusions: FDTD analysis of the RF field penetration has demonstrated that the same RF coil has different performance in human liver and brain imaging due to their different electromagnetic properties and geometric shapes. The liver has relatively irregular geometry and high conductivity, which impedes the RF fields of the coil, leading to decreased penetration. Human brain has high permittivity and relatively regular geometry, therefore the dielectric resonance becomes dominant at ultrahigh frequency and helps to increase the RF penetration. These research findings would be helpful in RF coil designs for human MR imaging applications where the RF penetration or imaging coverage is a concern.

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