FDTD simulations of RF inhomogeneities in ultrahigh-field MRI systems of up to 11.7 T

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Introduction

Recent advances in superconducting magnets and RF coils have realized ultrahigh-field MRI systems of up to 9.4 T [1], and several research groups have plans for developing 11.7 T systems. These ultrahigh-field systems have numerous advantages, such as acquisitions of precise functional and diffusion images, and imaging of non-proton nuclei. The technical challenges in the development of ultrahigh-field systems include inhomogeneities of RF fields as well as designs of superconducting magnets and RF coils. The NMR frequency reaches 500 MHz at a magnetic field strength of 11.7 T. At this high frequency, the skin effect causes a decrease in the signal intensity at the center of the subject's body, whereas the dielectric resonance effect causes an increase in the signal intensity at the center [2]. These contradictory effects result in a complicated signal distribution. A quantitative estimation of the signal distribution is essential for a prior evaluation of the advantages of ultrahigh-field MRI systems. The purpose of this study is to investigate the signal inhomogeneities in ultrahigh-field MRI systems using numerical simulations. Comparisons of signal inhomogeneities were made between circular and linear RF polarizations, and between protons and other nuclei.

Methods

Figure 1 shows a numerical model of the human head and a birdcage-type RF coil for producing a circularly polarized RF magnetic field. Each tissue in the model has its own dielectric constant and conductivity [3]. The dielectric constant and conductivity were dependent on the frequency of the RF magnetic field. The numerical simulation was based on the finite difference time domain (FDTD) method. The model was 42 cm in width and 47 cm in height, and was divided into 4-mm-square cells. Each cell had x and y components of magnetic fields, and a z component of the electric field. The birdcage-type RF coil had 8 wires and the diameter of the coil was 18 cm. The NMR frequencies ranged from 64 MHz to 500 MHz, which corresponded to magnetic field strengths ranging from 1.5 T to 11.7 T. The difference in phase between adjacent wires was $\pi/4$. A linearly polarized RF magnetic field was produced from a saddle-type coil whose diameter was 18 cm. The following rotating frame RF field B_+ was calculated from the x and y components of the rest frame magnetic field.

$$B_+ = \left(B_x + iB_y\right)/2 \qquad (1)$$

The signal intensity of spin-echo images was calculated using the equations described in our previous paper [2].

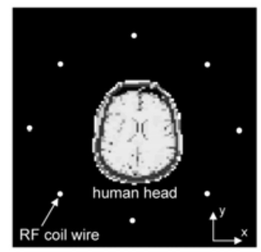

Fig. 1: Numerical model of the human head and an RF coil.

Results and Discussion

Figures 2(a)(b)(c) show the amplitudes of the rotating frame magnetic field B_+ at NMR frequencies of 64 MHz, 200 MHz, and 500 MHz (corresponding to magnetic field strengths of 1.5 T, 4.7 T, and 11.7 T, respectively). Figures 2(d)(e)(f) show phases of B_+ at these NMR frequencies. The magnetic field at 64 MHz had homogeneous distributions of amplitude and phase. An increase in frequency resulted in a severe inhomogeneity in the RF magnetic field. The magnetic field at 200 MHz had a high magnetic field at the center of the head. The magnetic field at 500 MHz exhibited a complicated amplitude distribution. An increase in the frequency caused a phase delay at the center of the head. The amplitude at 500 MHz ranged from 0.04 μT to 1.19 μT in the area of the human head.

Figures 3(a)(b)(c)(d) show estimated spin-echo images at 64 MHz, 128 MHz, 200 MHz, and 500 MHz, respectively. As expected from the magnetic field distribution, the increase in the NMR frequency caused inhomogeneities in the images.

Previous studies indicated that inhomogeneity appears when the wavelength is comparable to or smaller than the size of the human head [2]. Wavelengths in typical tissue (ε_r=77) at 64 MHz and 500 MHz are 53 cm and 6.8 cm, respectively and our results are consistent with those previous studies.

Figures 4(a)(b) show images obtained by linearly polarized RF magnetic fields. The signal inhomogeneity highly depended on the direction of RF polarization. The linear polarizations resulted in more complicated inhomogeneity in comparison with the circular polarizations (figure 3(d)).

Figure 5 shows signal inhomogeneities in images of the proton (^{1}H) and other nuclei. The ^{1}H and ^{19}F images exhibited severe inhomogeneities due to their high frequency, whereas ^{23}Na, ^{13}C, and ^{17}O exhibited relatively homogeneous signal distributions. The results suggest that ultrahigh-field MRI systems are particularly useful for quantitative measurements of non-proton nuclei. Quantitative analyses of the proton images require technical developments in RF coil designs and image processing for suppression of the signal inhomogeneity.

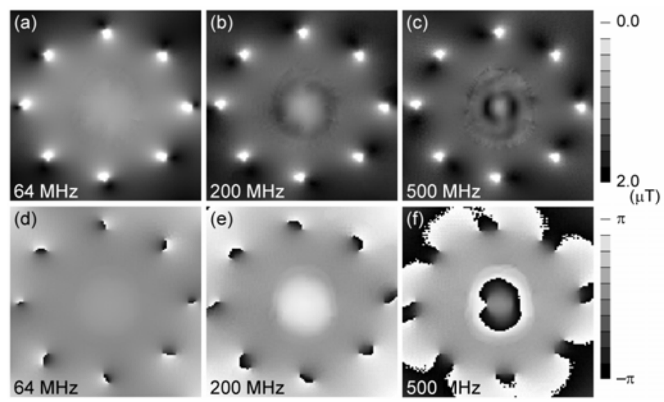

Fig. 2: (a)(b)(c) Amplitudes and (d)(e)(f) phases of RF magnetic fields at NMR frequencies of 64 MHz, 200 MHz, and 500 MHz.

References

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[3] www.brooks.af.mil/AFRL/HED/hedr/dosimetry.html

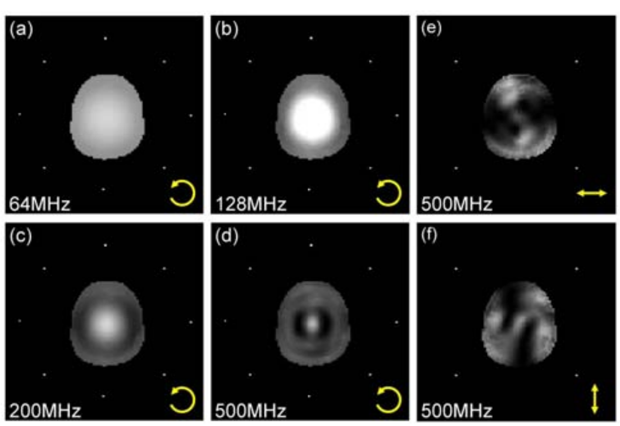

Fig. 3: MR images resulting from (a)(b)(c)(d) circularly polarized and (e)(f) linearly polarized RF magnetic fields

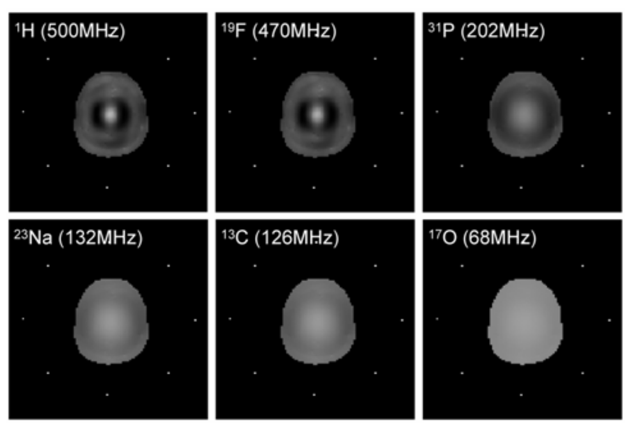

Fig. 4: MR images of the proton and other nuclei at 11.7 T.