Improvement of Spatial Resolution in Calculated Magnetic Field Perturbations Induced by Low Magnetic Susceptibility Devices for the MRI Image Simulator

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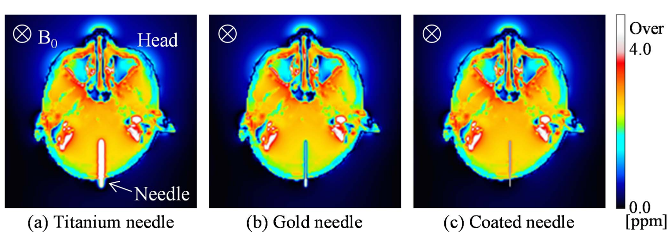
Introduction: Magnetic field perturbations induced by devices with low magnetic susceptibility produce artifacts in MR images. These artifacts cause serious problems for MR-guided therapeutic procedures. The effects of the devices on the perturbations need to be evaluated. However, the spatial resolution for field calculations is insufficient because of computer memory limitations. To overcome this challenge, we developed a computer code based on the superposition principle to increase the local resolution and on expansion of the calculation volume with extrapolation. We successfully applied the method to a head-sized numerical model.

Methods: Three-dimensional field perturbations were calculated using Marques' method [1]; this is based on a combination of Maxwell's equations, rotating coordinates, and the Fourier transform. The devices used in an MR magnet bore frequently have very fine and complex structures, so a submillimeter resolution is necessary to evaluate the effects of the devices on the images. However, an unattainably large amount of computer memory (20 TB) is necessary to treat the human-sized model using a 0.05 mm resolution and 384^3 mm^3 calculation volume. Thus, we propose an efficient method that utilizes superposition of higher-resolution fields for only the devices and lower-resolution fields for the surroundings. The two fields are connected at the boundaries, so the fields induced by devices must be attenuated to a negligible magnitude at the boundaries. However, increasing the resolution leads to reduction of the calculation volume. Therefore, it is necessary to expand the calculation volume to the range at which the fields decay to nearly zero. Expansion of the calculation volume is realized by extrapolation with a low-resolution field. Because the devices produce very complex perturbations with positive and negative polarities depending on the direction of the static magnetic field, we used a method that combines small multiple voxels with a large voxel by integrating the magnetic susceptibility distributions in these voxels. The combined voxels stably produce a large calculation volume for any perturbation. To show the effectiveness of the method, perturbed fields produced by a needle composed of two kinds of materials with different polarities of magnetic susceptibility were calculated.

Results: Figure 1 verifies the superposition principle of perturbed fields calculated by the computer code. The fields simultaneously calculated from the two spheres correspond to the addition of the two fields calculated individually (χ_1 = -9.05 ppm, χ_2 = -4.53 ppm, resolution = 1 mm, and calculation volume = 256^3 mm^3). Figure 2 shows the result of the calculation volume expansion. A single large voxel was obtained by adding eight small voxels and was used to produce a large calculation volume of 25.6^3 mm^3 with a 0.1 mm resolution. This field was combined with a higher-resolution field with a 0.05 mm resolution. The errors over the extrapolated volume were less than 0.1%. These errors were evaluated by comparing the calculated fields with an analytical solution. Figure 3 shows the perturbations calculated from needles of 60 mm length and 1 mm diameter: (a) titanium needle, (b) gold needle, and (c) gold needle coated with a thin titanium layer of 0.044 mm thickness. The perturbations were obtained by dividing the needle into six parts each of 10 mm length and superposing all the results with a 0.05 mm resolution (the thickness of the coating layer was approximated as 0.05 mm). Figure 3d shows the profiles on AB. Because the susceptibility of titanium is opposite in polarity to that of gold and the coated needle was designed to cancel out the integration of the susceptibilities, the perturbations induced by the coated needle were expected to be negligible. It is obvious that the coating layer canceled out the perturbations produced by the gold needle as verified by the higher-resolution calculations. Figure 4 shows the perturbations calculated from the 1 mm diameter needles penetrating into realistic, numerical human head model (size = 160 × 196 mm^2, voxel = 2^3 mm^3) [2]. Perturbations with a 0.05 mm resolution for the needles and a 2 mm resolution head model that included susceptibilities of white matter, grey matter, cerebrospinal fluid, muscle, and blood were used for the calculations. The susceptibility effects are clearly visible. The memory size needed in the calculation was less than 8 GB and computing time for each image was 1060 s (Intel Core i7, 3.2 GHz).



(a) Titanium needle (b) Gold needle (c) Coated needle

Fig.4: Perturbations produced by a numerical head model with needles penetrated into it: (a) titanium needle (χ = 183 ppm), (b) gold needle (χ = -34 ppm), and (c) gold needle coated with a thin titanium layer.

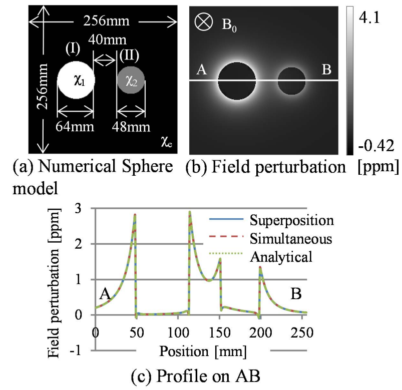


Fig.1: Verification of superposition: (a) numerical sphere model, (b) superposed field perturbation, and (c) profiles of perturbations on AB.

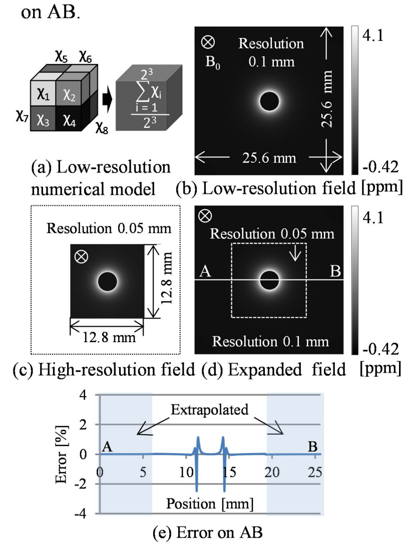


Fig.2: Result of extrapolation. A calculation volume is extended by a low-resolution field.

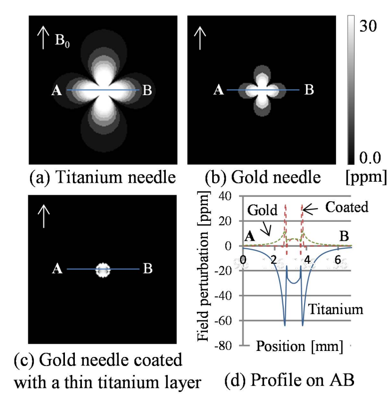


Fig.3: Perturbations produced by needles.

Conclusion: We successfully applied the method to the needles penetrated into the realistic head model and demonstrated the susceptibility effects of the device. The computer code should be useful in designing MR-compatible devices and evaluating the effect of the devices on the images without expensive experiments.

References: [1] J.P. Marques et al., Concepts Magn Reson Pt. B 2005; 25B:65–78. [2] N. Tomoaki et al., Phys Med Biol 2004; 49:1-15.
This work was supported by JSPS KAKENHI Grant Number 24500506.