Novel Modified 3D Shepp-Logan Phantom Model for Simulation of MRI Radiofrequency Coil Design

Masaki WATANABE,* Hitoshi MATSUZAWA,*,# Kenichi YAMADA,* Hironaka IGARASHI,* Tsutomu NAKADA*

Abstract Because radiofrequency (RF) coils used in magnetic resonance imaging (MRI) are specific for given regions of interest in the human head (HH), it is necessary to adjust the capacitance when setting the resonance frequency of MRI. Simulation-based development can reduce the number of components and manufacturing processes, but to obtain the same conditions as in the actual HH when RF coils are loaded, it is necessary to execute simulation of the head model under loading conditions. The HH model and spherical model are commonly reported for modeling the HH. In simulation, the HH model requires long calculation time because of its complicated shape. On the other hand, the calculated resonance characteristics of a spherical model are significantly different from those of the HH model, because the spherical model is oversimplified. We designed a new HH model by modifying the 3D Shepp-Logan Phantom model and evaluated its performance using a high frequency electromagnetic field simulator. Using our new head model in simulation, the approximate resonant frequency of the RF coil was calculated at 1/6 the calculation time of that when using the HH model, and the actual loading condition of the HH was reproduced.

Keywords: MRI-RF coil, HFSS, human head model, 3D Shepp-Logan Phantom model.


1. Introduction

For human 7T magnetic resonance imaging (MRI), it is necessary to develop homemade radiofrequency (RF) coils specific for arbitrary regions of interest, such as the inner ear and the cerebellum. In the RF coil design, the resonance frequency of the target can be set by adjusting the capacitance because inductance (L) is almost fixed when the coil shape is decided. The adjustment of capacitance based on simulation can reduce the number of components and calculation time.

However, to obtain the same conditions as the actual human head (HH) when the coils are loaded, it is necessary to execute simulation of the head model under loading conditions.

Therefore, for the development of the MRI RF coil, we designed a novel head model aiming to solve the issues of long simulation time when using the precise HH model and reduced accuracy when using the spherical six-layer (S6L) model [1].

The HH model designed from a three-dimensional (3D) MR image [2] and the S6L model [1] are commonly used to model the HH. To execute the simulation, it is necessary to express the object in a mesh (a set of small elements). The HH model requires a long calculation time [2] to solve an enormous number of mesh elements because of its complex multi-layered structure. Conversely, the calculation time for the S6L model decreases for the same calculation conditions because of a small number of meshes. However, the calculation result using the S6L model may be markedly different from that for the HH model because of its simplified shape, conductivity, and relative permittivity.

The original Shepp–Logan phantom was designed and reported for image evaluation of computerized tomography (CT) [3]. Several researchers have modified the Shepp–Logan phantom for use in MRI [4–6]. Koay et al. [4] reported a basic framework for constructing a 3D analytical MRI phantom in the Fourier domain to test image reconstruction algorithms. Kasten et al. [5] demonstrated the expediency of rapid prototyping for generating a flexible class of MRI and MRS phantom designs. Gash et al. [6] presented their analytic k-space representations after modification for MR physics, such as T1 and T2 relaxation times. However, those reports were not intended for simulations for electromagnetic analyses, such as calculating the reflection coefficient.
(S11) or Q values.

The aim of this study was to evaluate a new modified 3D Shepp-Logan Phantom (M3D) model, which is a new phantom model with the advantages of shortened calculation time as the S6L model, combined with precise simulation capabilities as the HH model.

2. Materials and Methods

2.1 Electromagnetic simulation

Simulation was executed using the High Frequency Structure Simulator (HFSS, ANSYS, Canonsburg, PA, USA) software [7, 8] and core i7-5820K 3.30 GHz processor, 128 GB RAM, Windows 10 Pro 64-bit. The HFSS created the mesh with the adaptive auto mesh function, and calculated the S11 for the specified frequency using a 3D full-wave finite element electromagnetic field solver in the frequency domain [8]. The simulation was executed by setting the feeding port to 50 Ω, the input power to 1 W, and the air space (which is the radiation space) to λ/4 in all directions to prevent reflection.

The RF coil model (surface coil) was designed as copper with a conductivity of 5.8 × 10⁷ S/m and a thickness of 0.035 mm.

The RF coil model was used for S11 simulation under loading condition in the HH, S6L, and M3D models. The capacitance used to tune and match the RF coil model was the same in all simulations. The center of the RF coil model was set at the outermost of the equatorial plane of the M3D and S6L models, and at the external acoustic foramen of the HH model (Fig. 1). However, no head model was in contact with the RF coil model.

In addition, the same calculation conditions were used in each model as follows.

For each head model, the mesh was created automatically, the solution frequency was 298.0 MHz, the maximum number of passes was six, the maximum delta S (judgment of mesh validity) was 0.01, and the maximum refinement per pass (rate of mesh increase) was 30%. S11 calculated using those meshes had an effective range 250–350 MHz and error tolerance of 0.5%. If the condition of error tolerance was not satisfied, the analysis was ended after 250 iterations.

2.2 Human Head Model

The HH model was designed based on the image data of one volunteer (male, aged 22 years) in our previous study (approved by the Ethics Committee of Niigata University) using 3D fast spoiled gradient echo (FSPGR) sequence (FOV = 20 mm, TR/TE = 7.4/3.0 ms, TI = 450 ms, thickness/gap = 1.5 mm/0.0 mm, NEX = 1, FA = 20°, matrix size = 256 × 160, and plane = axial) with the 3T MRI Signa LX (GE Healthcare, Waukesha, WI, USA).

The HH model was manually classified for each tissue, specifying the relative permittivity and conductivity (Table 1) based on the method reported previously [2], by adjusting the window level and window width of the image data (Fig. 1).

2.3 Spherical Six-Layer Model

The S6L model was designed with a total of six tissues (Fig. 1) by specifying the relative permittivity and conductivity (Table 2).

2.4 Modified 3D Shepp-Logan Phantom Model

The M3D model was classified into a total of nine tissues (Table 2). The brain parenchyma was classified into cerebral gray matter, cerebral white matter and cerebellum. The M3D model had an ellipsoid shape like the 3D Shepp-Logan Phantom model, and the vertical diameter was set at 1.1 times the horizontal diameter (Fig. 1). The brain gray and white matter had hemispherical shape and were located at the top of the head. The cerebellum was
located at a lower and rear position of the head [central coordinates: \((x, y, z/\text{uni} = 0, -20, -10)\)].

3. Results

3.1 Human Head Model

The HH model simulation results showed that resonance frequency was 298.0 MHz, \(S_{11}\) parameter was \(-12.5\) dB, \(Q\) value was 11.68, and calculation time was 15 h (Fig. 2, red curve).

3.2 Spherical Six-Layer Model

The S6L model simulation results showed that resonance frequency was 301.0 MHz, \(S_{11}\) parameter was \(-35.58\) dB, \(Q\) value was 35.41, and calculation time was 2.5 h (Fig. 2, green curve).

3.3 Modified 3D Shepp-Logan Phantom Model

The modified 3D Shepp-Logan Phantom Model simulation results showed that resonance frequency was 297.0 MHz, \(S_{11}\) parameter was \(-8.45\) dB, \(Q\) value was 10.06, and calculation time was 2.5 h (Fig. 2, blue curve).

4. Discussion

In the simulation results for the M3D model, resonance frequency, \(S_{11}\) parameter, and \(Q\) value approximated those of the HH model, and the calculation time was shortened to \(1/6\) of that of the HH model. In contrast, the S6L model was unsuitable for modeling because of significant difference in the simulation result compared with that of the HH model. The final decision to use a coil for the living HH required simulation including SAR [9]. However, in determining the steps of resonance frequency, it is necessary to shorten the calculation time because the simulation is repeated after changing capacitance. We designed the M3D model, which contributed to shortening of the calculation time in simulation.

There is a limitation that warrants mention in this study. We concluded the proposed M3D model as a good approximation based on only one simulation result. Because the loading state changes considerably among patients in clinical MRI, we were not able to conclude precisely whether the proposed M3D model is the best approximation. Additional investigations are required to confirm this and to further develop this model to meet the needs of precise coil design.

In this study, a simple loop coil model was used to explain the efficiency of the M3D model. However, in the future, when designing a phased array coil with multiple elements, the HH model will involve an enormously increased calculation time and the calculation results of the S6L model may differ greatly from those of the HH model. We reason that the M3D model increases the accuracy of simulation results in the design of phased array coils.
5. Conclusion

In developing MRI-RF coils, determining the capacitance based on simulation can reduce the number of components and manufacturing steps. However, simulation of the HH model with loading increased the calculation time. On the other hand, the simulation result of the S6L model was considerably different from that of the HH model. The simulation result of the M3D model was a good approximation of that of the HH model, and the calculation time was significantly shortened, and the model faithfully reproduced the actual loading conditions of the HH.

Conflict of interest

We have no conflicts of interest with any companies or commercial organizations, based on the definition of Japanese Society for Medical and Biological Engineering.

References