Technique using implicit fairing and specific absorption rates to improve spatial resolution of whole-body human voxel models exposed to plane waves in GHz bands

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Abstract

To evaluate the safety of electromagnetic fields above 3 GHz, we devised a technique for developing arbitrary high-resolution models in which the irregularities between tissue boundaries are smoothed. The quality of the improvement was estimated by using human voxel models with a 1-mm resolution that had been developed with the improvement technique from models with a 2-mm resolution. We found that the improvement technique can smooth the irregularities between tissue boundaries and can keep the masses of the original tissue models relatively unchanged. In this paper, we also present the basic specific absorption rate characteristics of the improved human voxel models with 1-mm resolution under exposure to E-polarized plane waves from 1 GHz to 5 GHz. We found that the whole-body averaged SAR was dependent on the structure (smoothness of tissues and/or skin thickness) of the human voxel models in the GHz bands.

1. Introduction

There has been increasing concern about the safety of radio-frequency (RF) electromagnetic fields (EMFs). The safety of such RF-EMFs is evaluated with the specific absorption rate (SAR). Recently, various anatomically realistic human voxel models for SAR dosimetry have been developed, and many numerical simulations using such models have performed [1-3]. We have developed various 2-mm-resolution anatomically realistic models of Japanese [3-5]. These models enable us to evaluate exposure to high- frequency electromagnetic radiation (up to 3 GHz).

However, we anticipate that wireless communication devices will be used at frequencies above 3 GHz in the near future. Therefore, we need to develop higher resolution anatomically realistic models to make evaluations of such high frequencies. Developing a new high-resolution model by using medical imaging devices requires a tremendous amount of time, so they are constructed by using image processing techniques on existing anatomically realistic human voxel models [6]. For example, the spatial resolution of the models becomes twofold when the size of the voxels of the models is decreased to one-half. Therefore, it is possible to increase the applicable frequency about twofold. If the staircase shape of the curvature boundaries is conserved, however, errors due to rough modeling might become significant at higher frequencies.

To solve the above problem, we created a technique for developing arbitrary high-resolution models while smoothing the irregularities between tissue boundaries. We also measured the basic characteristics of EMF exposure, i.e., the SAR in the whole-body exposure to plane waves above 1 GHz by using human voxel models that were developed with this improvement technique.

2. Technique for improving the resolution of human voxel model

2.1. Method

Smoothing filters cannot be used to smooth out irregular boundaries in the human voxel model, because the model uses the voxel values as an index (ID) that represents the human tissues. Therefore, the voxel data (volume data) is converted into mesh data for each tissue in the human voxel model. Implicit fairing [7], which is a smoothing technique for irregular meshes, is performed on the mesh data of the model. The Laplacian is calculated at each vertex in the mesh fairing by using an umbrella operator and the vertex is moved as shown in Fig. 1. The Laplacian operator is repeatedly used to remove the local irregularities of the human voxel model and to keep only the comprehensive irregularities (Fig. 2). Finally, the mesh data are reconverted into volume data of arbitrary resolution.

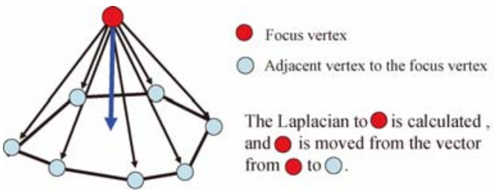

Fig. 1 Laplacian operator

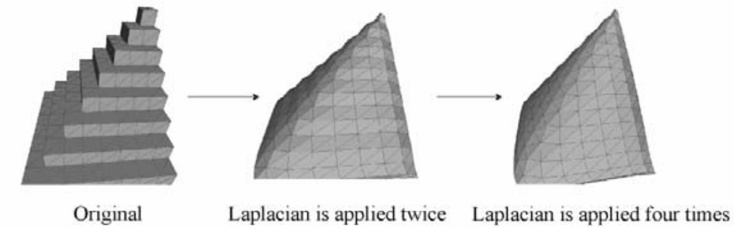

Fig. 2 Example of mesh fairing

2.2. Experiment

We performed computational experiments on our improvement technique using two human voxel models of a Japanese adult male and child [3],[4]. The models consist of 2 x 2x 2 mm voxels, i.e., 2-mm resolution, and have 51 different tissues. The higher resolution models with 1-mm resolution were created from the original models by applying our improvement technique. Figure 3 shows the surface images of the original model and the improved high-resolution model of the Japanese adult male. The surface of the improved model was smoother than that of the original model. In addition, comprehensive irregularities, such as around the eyes and lips of the model, are kept on the improved model, but local irregularities are smoothed out. Figure 4 shows the coronal images of these models. The tissues in the improved model are very smooth compared with those of the original model.

SAR represents the amount of RF energy absorbed per unit weight of the body and is influenced by the masses of the internal tissues. Therefore, we compared the internal tissue masses of the improved models and the original models. The body weight of the improved child model was 13.81 kg and was 0.25 kg heavier than the original model. Mean deviation of masses of each tissue between both models (except small tissues within 10 g) was 6%. For the adult male model, the difference in body mass between the improved (68.8 kg) and the original (67.8 kg) models was 1.00 kg.

From these results, we found that our improvement technique of the spatial resolution of human voxel models can smooth the tissue boundaries of the models and can keep the masses of tissues of the original models.

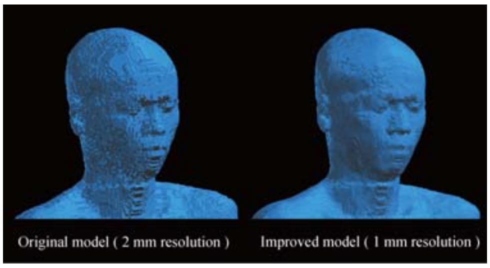

Fig. 3 Surface images of human voxel models

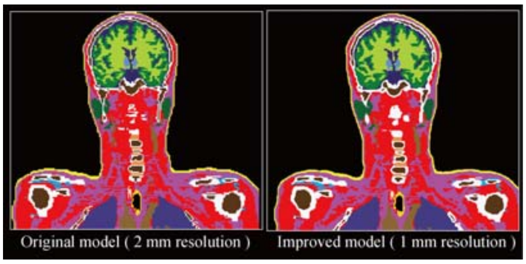

Fig. 4 Coronal images of the models

3. Numerical simulation

3.1 Simulation models and calculation conditions

The finite-difference time domain (FDTD) method was used to calculate the SARs of high-resolution anatomically human voxel models for whole-body exposures to E-polarized plane waves from 1 GHz to 5 GHz. The incident waves were assumed to propagate from the anterior to the posterior relative to the models, which were assumed to be in free space. The incident power density was 1 mW/cm^2, which is the reference level for occupational exposure to electromagnetic fields in the very high frequency (VHF) band [8]. Perfectly matched layer (PML) boundary conditions (eight layers) were assumed for the all boundaries of the calculation region. The PML boundaries were set 60 mm away from the nearest parts of the model.

This study used adult male and female and 3-year-old child models of Japanese [3],[4]. Electromagnetic properties corresponding to the tissues and organs of these models were obtained from the 4-Cole-Cole analysis reported by Gabriel [9]. Peyman et al. reported that there is a difference in the dielectric properties of each tissue and organ between young and adult rats [10]. However, Wang et al. reported that differences in the electrical properties of children have only minor effects on the local SAR [11]. Therefore, we assigned the same electrical properties for each tissue and organ of these models.

3.2 Results and Discussion

The frequency characteristics of whole-body averaged SARs of the improved 3-year-old child model with 1-mm resolution relative to those of the simple scaled model with 1-mm resolution and the original model with 2-mm resolution are shown in Fig. 5. The simple scale model was constructed by quartering the size of the original voxels (2-mm resolution). The whole-body SARs of the improved model are the lowest values for each frequency. The deviation for the whole-body averaged SAR between these models is within 3 % at 1 GHz. However, the difference between the whole-body averaged SARs of these models tends to become larger at higher frequencies. The deviation between the whole-body averaged SARs of the improved model and that of the original model rises as high as 18 % at 3 GHz. In addition, mean deviation between the whole-body averaged SAR of the improved model and that of the simple scaled model at frequencies higher than 4GHz is 18 %. These results suggest that the effect of smoothing can affect the whole-body a

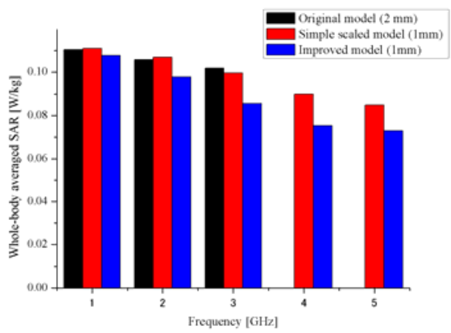

Fig. 5 Frequency characteristics of whole-body averaged SAR of a 3-year-old child model

Table 1. Comparison of skin masses of model with 2-mm skin thickness model and one with 1-mm skin thickness.

Model	Mass (g)		
	2-mm skin thickness	1-mm skin thickness	reference
Male	4218 (1.76)	2417 (1.01)	2400
Female	3473 (1.93)	2047 (1.13)	1800
3-year-old	1259 (2.09)	754 (1.25)	601

It is known that energy absorption occurs mainly at the body surface, i.e. skin tissue, in the GHz bands. However, the skin masses of the original models are overestimates. These errors are caused by constructing models with voxels of 2 x 2 x 2 mm^3, while the actual thickness of skin is less than 2 mm on most body parts. Therefore, we constructed adult male and female and 3-year-old models with the 1-mm skin thickness on the basis of the models with 1-mm resolution and 2-mm skin thickness that were developed with our improvement technique. Table 1 shows the skin masses of each model. The result indicated that the models with 1-mm skin thickness are closer to the reference values [12] than the models with 2-mm skin thickness. Figure 6 shows the frequency characteristics of whole-body averaged SAR for these models. The whole-body averaged SARs of the models with 1-mm skin thickness are higher than those of the models with 2-mm skin thickness for each frequency. The differences between the whole-body averaged SARs of these models tend to become larger at higher frequency and the deviations at 4 GHz are over 24 % (though the deviations are very small in 1 GHz (3%)). Regarding the whole-body averaged SAR in the GHz bands, these results suggest that the dependence on the skin thickness of the human voxel models becomes larger as the frequency increases.

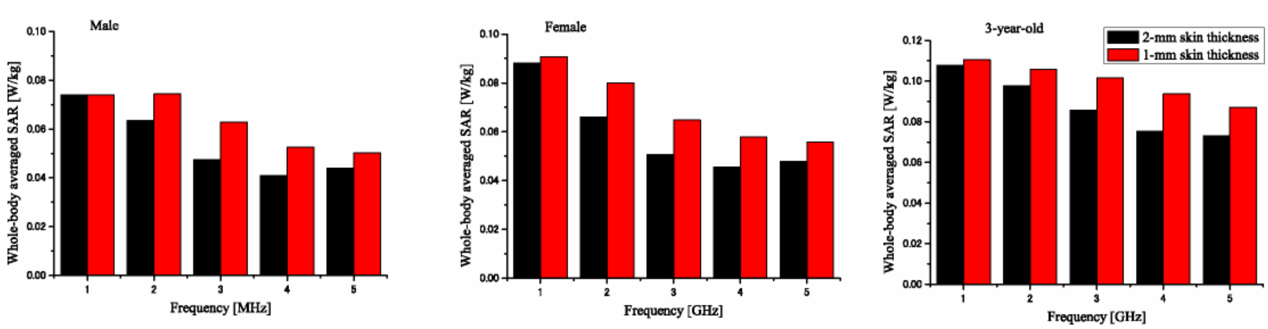

Fig. 6 Whole-body averaged SARs of human voxel models with 2-mm and 1-mm skin thicknesses

4. Conclusion

We proposed a technique for developing arbitrary high-resolution models in which irregularities between tissue boundaries are smoothed. We conducted experiments on Japanese human voxel models that confirmed the improvement technique can smooth out the irregularities between tissue boundaries of the models and can keep the masses of each tissue the same as in the original models. We also presented the basic SAR characteristics of the improved Japanese human voxel models with 1-mm resolution exposed to E-polarized plane waves in the GHz bands. As a result, we found that the structures (smoothness of tissues and/or skin thickness) of the human voxel models are important factors to accurately estimate the whole-body averaged SAR in the GHz bands.

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7. References

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