5 Research on Biological Effects of Radiofrequency Radiation and on Evaluation Methods of Compliance with Radiofrequency Radiation Protection Guidelines

5-1 Studies on Dosimetry of Human-Body Exposure to Electromagnetic Fields

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Numerical simulations are required to estimate specific absorption rate (SAR) in a human body exposed to high-frequency electromagnetic fields in order to evaluate the safety of the exposure. Development and improvement of numerical human models to be used for such numerical simulations and improvement of numerical calculation techniques for complex exposure conditions have been studied in NICT. Dielectric properties of biological tissues in millimeter-wave band have furthermore been studied with development of measurement systems. These studies contribute to safety environment with convenient radiofrequency use.

Keywords
Dosimetry, SAR, Voxel human model, FDTD method, Millimeter wave, Electric constants

1 Introduction

People in all walks of life are now using radio waves in a wide variety of daily contexts, with cellular phones as merely one example. This increased use has led to growing concerns over the potential adverse effects of exposure to electromagnetic fields on human health.

Radio waves are a subset of electromagnetic waves, and according to the definition set forth in the Radio Law, correspond to electromagnetic waves having frequencies below 3 THz. However, generally, radio waves with frequencies below 300 Hz are referred to as extremely low frequency (ELF) and are often treated as an electromagnetic field rather than as radio waves. Exposure to an ELF electromagnetic field induces electric currents in the human body that may stimulate the nerves. This phenomenon is referred to as the stimulant effect.

Since the effects on the nervous system of electric current induced by radio waves above 100 kHz are not pronounced, the main concern with respect to radio waves in this range is not the stimulant effect, but rather the heating of human body tissues due to the absorption of radio energy. This is called the thermal effect, which is measured by specific absorption rate (or SAR; the amount of electromagnetic power absorbed by unit mass of a biological body). Since biological tissues appear to have virtually no magnetism (with a relative permeability of 1), the SAR of a biological body may be defined by the following equation (1).

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right) = \frac{\sigma |E|^2}{\rho} \quad \text{[W/kg]} \quad (1)$$

Here, dW is the energy (J) absorbed by an incremental mass (dm kg) of a biological body, σ (S/m) is the conductivity, E(V/m) is the strength of the electric field within the biological body, and ρ (kg/m^3) is the density of the biological body.

In order to evaluate the safety of radio-frequency radiation exposure for humans, we must make precise measurements of SAR in the human body. However, direct measurement of SAR within the body is problematic. Specifically, it is difficult to obtain data on electric field intensity in the body interior. To overcome this problem, NICT has developed voxel human models that precisely simulate the internal structure of human bodies, and studies on SAR measurement techniques are now underway through numerical simulations using these models (Section **2**).

Electromagnetic field analysis simulations using the voxel human model involve large-scale numerical computation that requires several tens of GB of memory, and so a supercomputer is required for computation. However, even with the use of the supercomputer, the evaluation of various exposure conditions requires extensive machine time. NICT has thus installed a supercomputer system dedicated to electromagnetic field analysis using the voxel human models and is also devoting efforts to improving the method of numerical analysis (Section **3**).

When performing numerical analysis of an electromagnetic field, we must consider the electric properties of the individual tissues and organs that constitute the human body. Of the various studies presented to date on electric-constant evaluation of biological bodies by various research groups, a report by the U.S. Air Force Research Laboratory (AFRL)[1] is currently regarded as the most exhaustive and reliable reference source. However, most reports, including the AFRL report, target radiofrequency radiation in the microwave band having frequencies of several GHz and do not include measurements of electric constants of tissues in the millimeter-wave band at frequencies above 30 GHz. Since the use of radio waves in the millimeter band is expected to expand dramatically in the near future[2], NICT is currently undertaking studies on this range (Section **4**).

Summaries of these research themes will be given in the following sections.

2 Development and improvement of the voxel human models

2.1 Development of the voxel human models and publication of database

Recent advances in medical diagnostic technologies have facilitated the acquisition of tomographic images of the internal human body, and numerical human models composed of small block units have been developed based on the accumulated MRI image data. The unit blocks of models, featuring high spatial resolution on the order of several millimeters, are referred to as “voxels”, analogous to the use of the term “pixels” for image data.

In the past, numerous voxel models of the human head have been developed for SAR dosimetry, assuming exposure conditions of cellular phone use. However, various radio devices other than cellular phones will most likely be developed and worn on various parts of the body, and thus it is necessary to develop voxel human models for the entire body. Such models have already been developed for Caucasian males, but they cannot be used to represent Japanese males. Therefore, collaborative efforts have been undertaken by Kitasato University, Keio University, Tokyo Metropolitan

University, and NICT (known at the time of the study as the Communications Research Laboratory) to develop whole-body voxel human models for the Japanese male and female, by collecting MRI images of adult Japanese volunteers of average build[3][4] (Fig. 1).

The male and female whole-body voxel models are composed of approximately 8 million and 6 million 2 mm voxels (three-dimensional blocks), respectively. Each voxel is labeled with tags representing 51 types of tissues and organs and assigned with the electrical properties of the respective tissue/organ; these properties are used in the numerical analysis of the human electromagnetic field.

These were the first whole-body voxel models developed for Japanese adults, and the first in the world for the female adult. Thus, the models were widely recognized by researchers both in Japan and abroad. Furthermore, these models can be adapted for numerical simulations in various fields of research simply by defining the set of physical parameters for the voxels for each tissue and organ type. For example, the model may be used for radiation therapy analysis by defining the appropriate radiation absorption constants, or for simulation tests of human damage in crash tests by defining elastic coefficients for each tag type. Various research institutes, both domestic and foreign, have contacted us for information regarding the use of these voxel human models; as a result NICT has begun the free distribution of the models for non-commercial, research purposes, beginning in November 2004[5]. The male and female models are named TARO and HANAKO, respectively.

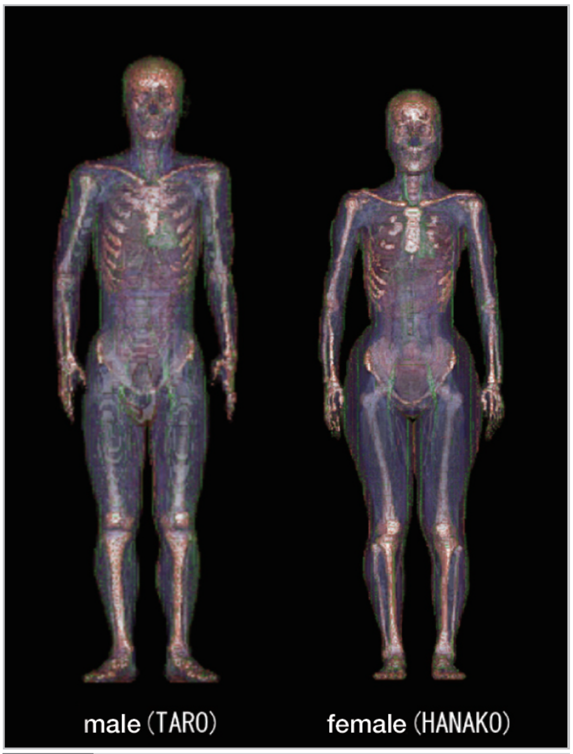


Fig.1 *Whole-body voxel human models for the average Japanese male and female*

2.2 High-performance voxel human models

Most whole-body human voxel models developed to this point, including the ones described above, represent humans in a standing position (or lying supine). However, in the ubiquitous network society anticipated for the future, radio communication devices will be used on various parts of the body in various positions, and so it will be necessary to perform SAR measurements assuming the actual positions taken by the human body while the devices are in use. Thus, NICT is currently working to improve existing models to create high-performance voxel human models that can accommodate various postures (Fig. 2).

Presently, cellular phones are widely used not only by adults but by juveniles as well, and so there has been a growing need to evaluate SAR in children. However, given the ethi-

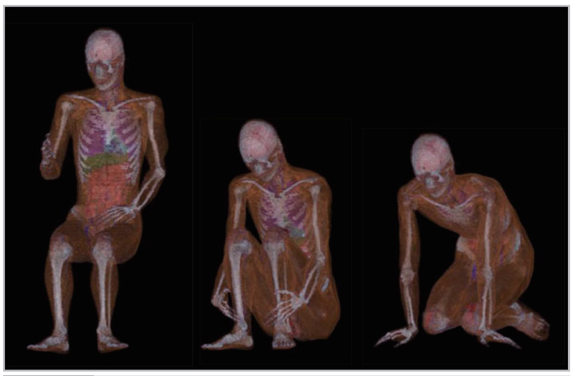


Fig.2 *Examples of models capable of postural changes*

cal restrictions on restraining children within an MRI unit for extended periods solely for research purposes, no whole-body voxel models have been developed for children. To overcome this problem, NICT has undertaken a joint research effort with the Nagoya Institute of Technology to develop a method of creating whole-body child voxel models by modifying the adult male model, including the internal structures. By taking measurements of the physique and size of children, we have succeeded in developing voxel models as precise reconstruction of children bodies (Fig. 3).

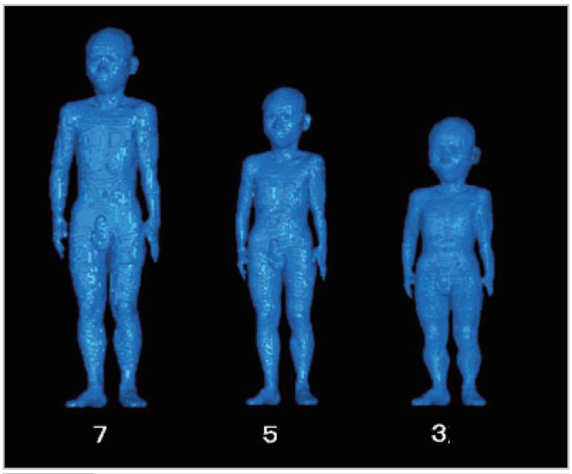


Fig.3 *Examples of whole-body child voxel models*

In addition to the projects cited above, efforts are now being made to improve the spatial resolution of whole-body human voxel models, to add and modify identified tissues and organs, and to develop voxel models for pregnant women. Databases for these high-performance models are planned for publication after undergoing the appropriate medical reviews.

3 Improvement of numerical calculation techniques

3.1 Introduction of a supercomputer

As stated above, electromagnetic field analysis using whole-body voxel human models requires huge memory resources of up to 20-30 GB. In order to carry out such large-scale numerical simulations efficiently, in 2003 NICT installed a supercomputer dedicated to these computations using human voxel models. The system is connected to and managed as a part of the NICT shared supercomputer (NEC SX-6) system. The system features eight CPUs and 64 GB of memory, and is available to registered users for whole-body voxel human model calculations, without any restrictions as to machine time. (When there are no jobs requested by registered users, the supercomputer is made available to general users with a maximum machine time limit of eight hours).

3.2 Modifications to the numerical analysis method

The finite-difference time-domain (FDTD) method is generally used for analyzing SAR distribution in human bodies exposed to electromagnetic fields. The FDTD method enables the simulation of temporal changes from initial conditions to a transitional period and finally to the steady state, by employing finite differences as approximations for spatial and temporal derivatives that appear in Maxwell's equations. This approach enables electromagnetic field analysis for the lossy dielectric medium of the human body, analysis that cannot be easily performed using techniques such as the method of moment (MoM).

When performing SAR evaluations for cellular phones and other radio terminal devices used in close proximity to the human body, we must create high-precision models not only of the human body but also of the antenna structures that emit the radio waves. However, complex antenna structures with multiple curves, such as the helical antenna, could not previously be modeled with high precision at spatial resolutions of several millimeters. In contrast, the MoM allowed for modeling of antenna structures with relatively high precision. This resulted in a proposed hybrid method in which calculations for the antenna portion are made using the MoM and those for the human body are made using the FDTD method. However, the complexity of iterating the MoM to and from the FDTD method had prevented the hybrid method from being employed in the calculation of human SAR in practical cases involving complex antenna structures. To overcome this problem, a collaborative effort was undertaken by NICT, Chuo University, and the Tokyo University of Agriculture and Technology to improve the conversion process; the aim was to develop a simplified procedure for numerical analysis with the hybrid method, a combination of the MoM and the FDTD methods[6]. Figure 4 shows the SAR distribution in the human head in close proximity to a dipole antenna.

The electromagnetic field around a dipole antenna can be calculated with high precision by the FDTD method, and the consistency of calculation results between the FDTD method and the present hybrid method support the validity of the latter. Studies are now being conducted on SAR measurements by the hybrid method for human bodies located in close proximity to complex-shaped antennas.

It is known that exposure to VHF radio waves induces a phenomenon known as whole-body resonance, in which the human body acts as a resonant antenna due to the fact that the wavelength of VHF radio waves are comparable with the height of the human body[7]. Extremely strong electric currents are induced, particularly in the ankle region, when the human body is in the standing position on the ground, and results in significantly large local SAR in the ankle. In past studies, the ground plane had been regarded as a perfect conductor wall, but it is now known that the actual electrical properties of the ground resemble those of low-loss dielectrics. In order to incorporate the low-loss ground plane in the FDTD model, it is necessary to include more than several meters of ground layer in the computation domain, which results in a dramatic increase in both the memory and machine time required for computation. This has essentially prevented human SAR calculations incorporating an assumed low-loss ground plane. To overcome this problem, a collaborative effort was undertaken by NICT and the Tokyo University of Agriculture and Technology to develop a surface impedance model for approximating the low-loss ground plane[8]. Figure 5 shows the induced electric current distributions in metal wires on the low-loss ground plane and in the human model.

Although the current distribution in the metal wire was fairly consistent with the results of FDTD calculations assuming a ground layer 5 m thick, significant deviations were observed in the distribution of electric currents induced in the human body in the foot and lower legs. This discrepancy probably results from the difference in boundary conditions between the human body and ground and between free space and the ground. Studies are now being conducted to improve the cal-

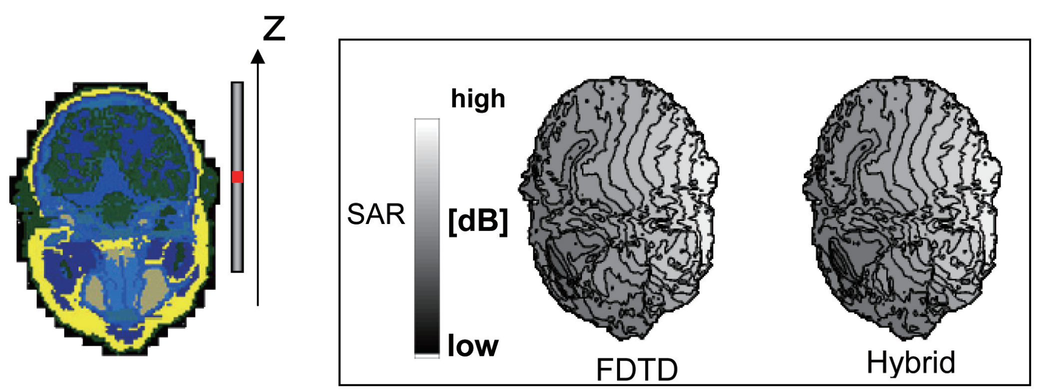
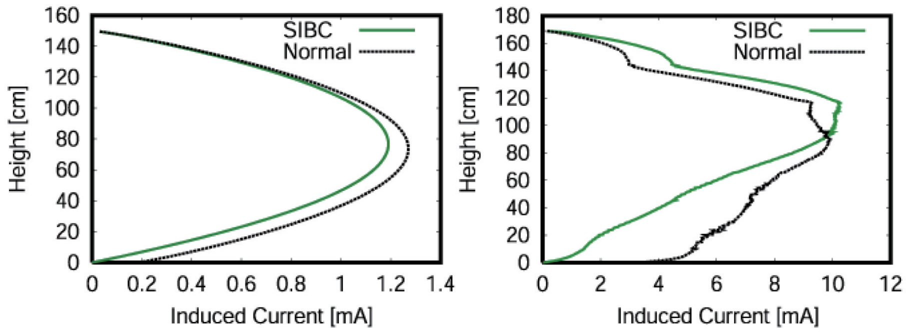


Fig.4 *Results of SAR calculation for the interior of the human head in close proximity to a dipole antenna*



(a) Metal wire (b) Human model

Fig.5 *Induced current distribution on the low-loss ground plane*

culation method for the case of a human body standing upright on the ground plane[9].

4 Dielectric constants measurement of biological bodies for the millimeter and quasi-millimeter wave bands

Several dielectric relaxation phenomena are associated with the electrical properties of biological bodies, including human bodies, causing them to display complex frequency characteristics. In the frequency range higher than several hundred MHz, the dominant phenomenon is the dielectric relaxation of water molecules, which resonate near 22 GHz at room temperature. The electrical properties of biological bodies are known to vary significantly depending on frequency and temperature in the frequency range of millimeter and quasi-millimeter waves[10].

The dielectric constants of biological bodies have generally been measured using an open-ended coaxial probe. However, measurements of dielectric constants in the millimeter-wave band were rendered difficult by the unsuitability of coaxial probes for this purpose. Therefore, NICT is developing a system for dielectric constants measurement in biological bodies using lens antennas[11]. Figure 6 shows the measurement system currently under development.

We are also conducting a dielectric constants measurement of blood using a recently marketed open-ended coaxial probe, which can take measurements up to 50 GHz (Fig. 7).

In the future, experiments will be performed to measure the dielectric constants of common samples using different measurement systems, in order to examine the validity of the various measurement methods. The results of these experiments will be used to construct

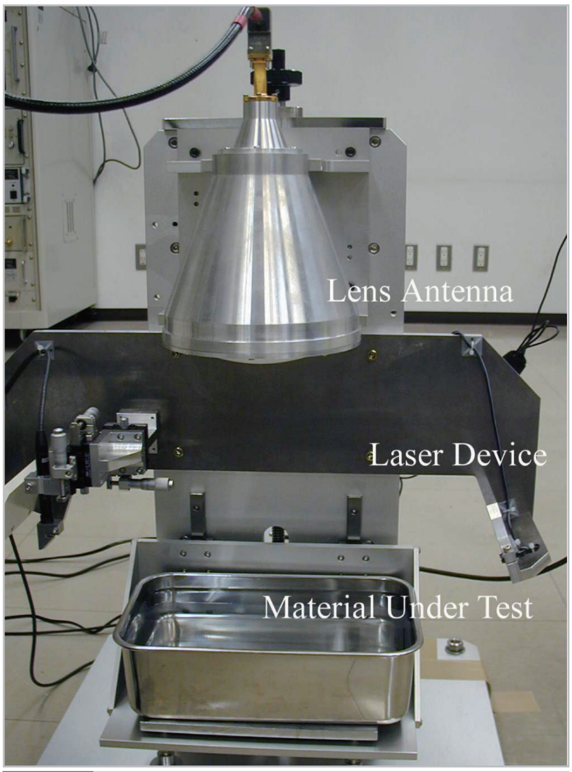


Fig.6 *Biological-body dielectric-constants measurement system using lens antennas*

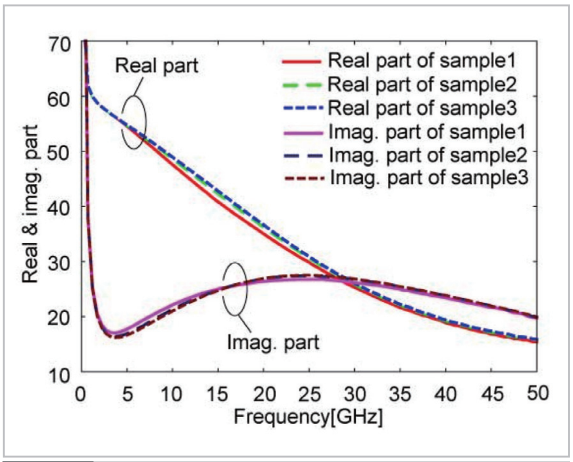


Fig.7 *Results of dielectric constants measurements of blood using the open-ended coaxial probe*

a highly reliable electric constant database.

5 Conclusions

The present paper summarizes the direction of research activities at NICT regarding the dosimetry of human-body exposure to radiofrequency radiation. In the anticipated future ubiquitous network society, radio waves will most likely be used in a variety of situations that we do not even imagine today. The development of high-performance voxel human models and improvement of numerical analysis techniques will be important in responding to these new radio wave applications and in performing the appropriate evaluations of the safety of radio-frequency radiation exposure. Further, by improving technology for measuring the dielectric constants—ones of the most fundamental physical parameters required for the dosimetry—it will become possible to improve the precision of the dosimetry to millimeter-wave band radio-frequency radiation, which is expected to expand significantly in the future. Although not mentioned in this paper, NICT is also conducting studies on electromagnetic field exposure in the intermediate frequencies generated by induction heating (IH) cookers and appliances and the effects of radiofrequency exposure on medical devices implanted within the body. Our goal in these R&D activities is to help establish an environment in which radio waves may be used safely and without anxiety.

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Enhancement and Sophistication of Human Voxel Models,

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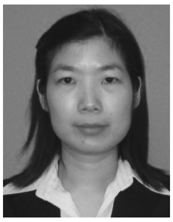

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Bioelectromagnetics