5-2 Review of Bio-EMC Studies

Soichi WATANABE, Kanako WAKE, Kaori FUKUNAGA, and Yukio YAMANAKA

Biological aspects of electromagnetic compatibility (Bio-EMC) have been studied by EMC Research Group of CRL. There are two main subjects in the field. One is related to rules and regulations of electromagnetic-wave hazards, especially development of standard estimation methods of electromagnetic power deposited in human bodies exposed to microwaves from cellular telephones or VHF-band radio waves. Another is development of exposure setups for laboratory animals used in biological studies on health effects of electromagnetic waves and their dosimetry. Novel phantoms are also being developed in order to perform highly accurate dosimetry in above studies. It is expected that these studies contribute development of compliance tests for radiofrequency protection guidelines and improvement of rationale of those guidelines, which consequently provides safety environment including appropriate radio wave applications.

Keywords

Radio-radiation protection guidelines, specific absorption rate (SAR), phantom, dosimetry, exposure setup for biological studies

1 Introduction

As can be seen from the explosive popularity of cellular telephones in recent years, wireless communication terminals have come into wide use among the general public. On the other hand, the increased use of devices employing radio waves has led to increased concerns about their effects upon human health.

A vast amount of research has been conducted to date regarding the effects of radio waves upon health, and based on these findings, guidelines for protection against radio waves have been set forth in many countries. In Japan, radio-radiation protection guidelines[1] were submitted by the TT-Council (Telecommunication Technology Council) of the Ministry of Posts and Telecommunications (presently, the Telecommunications Council of the Ministry of Public Management, Home Affairs, Posts and Telecommunications) in 1990, were partially revised in 1997[2]. These have been in effect as mandatory standards (the Enforcement Regulations of the Radio Law) since 1998, with, however, some elements of these guidelines excluded.

It is expected that through the rigorous application of the protection guidelines as mandatory standards (rather than as conventional voluntary standards), the environment under which the general public can use radio waves without anxiety will be regulated. However, in order to make the protection guidelines as mandatory standards practically, it will be necessary to establish a standard evaluation technique that is accurate, highly reproducible, and, as much as possible, simple. In addition, it is now urgently necessary to establish an international, standard evaluation technique, in light of the globalization of radio communications systems in recent years. Therefore, the International Electrotechnical Commission (IEC) established a Technical Committee (TC106) in 2000 to standardize techniques to evaluate the compatibility of radio-radiation protection standards.

Moreover, with respect to the health effects of exposure to electromagnetic waves from wireless communication devices (such as cellular telephones), although it is generally understood that sufficient protection can be achieved through the application of current standards, biological studies with higher accuracy must nevertheless be conducted, in light of probable effects of the long-term use of these devices. Thus, in 1996 the World Health Organization (WHO) initiated the International EMF Project, and continues to support international research activities. In Japan, the Committee to Promote Research on the Possible Biological Effects of EMF (Chairperson: Professor Shogo Ueno, the University of Tokyo) of the Ministry of Posts and Telecommunications (presently, the Ministry of Public Management, Home Affairs, Post, and Telecommunications) was established in 1997, promoting cooperative research projects among experts from various engineering fields as well as from the medical and biological fields.

The EMC Research Group of the Communications Research Laboratory, to which the authors belong, has been researching the biological effects of electromagnetic waves since 1997. It is making steady progress in research on techniques to evaluate the compliance of radio-radiation protection guidelines, as well as in the development of exposure setups to elucidate the biological effects of radio waves. This text describes the outlines of these research subjects.

2 Research on the evaluation of the compliance of radio-radiation protection guidelines

It is known that in terms of the effects of radio waves over a few hundred kHz upon the human body, the effects of heat (the thermal effects) generated by the electromagnetic-wave energy absorbed by the body is dominant. As an index for measuring the thermal effects of electromagnetic waves, the specific absorption rate is used, indicating the power absorbed by a unit weight of a given substance. The specific absorption rate is usually abbreviated as SAR. The unit of SAR is W/kg.

To evaluate the safety of radio waves (i.e., the thermal effect), first and foremost the SAR in the body must be accurately evaluated; radio-radiation protection guideline values are then specified based on the SAR characteristics in the human body. Therefore, our research group is pursuing research into dosimetry technology, whereby the SAR in the human body can be accurately evaluated.

2.1 Head SAR caused by the use of cellular telephones[3]

Cellular telephone use places the head in extreme proximity of a radio-wave-radiating antenna. The SAR distribution inside the head in such cases varies considerably, depending on a variety of conditions. In this context, the head SAR must be measured under actual operating conditions; in particular, the strong coupling of the antenna with the human head must be considered. A measuring system that satisfies this requirement is currently being developed. According to a recently standardized SAR measurement method[4], a head phantom[1] is used a loss-less dielectric shell imitating a head shape, filled with a liquid whose electric characteristics are equivalent to those of head tissues.

This standard measurement method takes into consideration the fact that highly reproducible measurement results will be obtained by precisely defining the head phantom shape and the position of the cellular telephone. However, the head phantom shape adopted under the standard measurement method has been defined based on statistical data for Europeans and Americans, and is considerably large relative to the average Japanese person. The validity of applying such a large head model to the Japanese has not been subject to rigorous examination. Thus, we are currently examining the relationship between head shape and the SAR in the head.

The measurement results of the SAR distribution in three kinds of head phantoms are shown in Fig.1. An European and American head phantom and a Japanese head phantom (A) are both constructed such that the ear pinna are made of a loss-less medium. The ears of both phantoms are the same shape, and in both cases one ear is pressed against the head, as in cellular telephone use. On the other hand, another Japanese head phantom (B) is constructed such that the ear pinna are filled with the same liquid as the cephalic part of the phantom, and are in a normal position (neither of the ears is pressed as in cellular telephone use).

As shown in Fig.1, with ear pinna of the similar material and shape, the SAR distributions of the European and American head phantom and of the Japanese head phantom are almost same. On the other hand, it is shown that with different ear pinna shapes (and identical cephalic parts) the two Japanese phantoms display a large difference in SAR distributions. Therefore, it is concluded that the SAR distribution in the head during cellular telephone use is not dependent on the shape (or dimensions) of the entire head but on the shape of the ear pinna closest to the cellular telephone.

Moreover, it has also been shown through studies with cellular telephone models of various shapes that the European and American phantom, which is large in size relative to the Japanese head, gives a maximum local SAR value that is either nearly equal to or larger than that of the Japanese head phantom. Accordingly, the use of this relatively large standard head phantom is deemed acceptable in terms of the safety evaluation of the compliance of standard values, as this phantom will result in an SAR value that is higher than the actual values for Japanese people.

In association with this research, we are also conducting research on the effect of the shape of the ear pinna[5], the effect of the support hand[6], and, additionally, an SAR measurement method for amateur portable wireless equipment[7][8].

2.2 Ankle SAR evaluation in VHF band[9]

In the VHF band (30-300 MHz), where the wavelength of the radio wave is comparable to the human body, E-polarized electromagnetic wave incidence to the human body can cause resonant phenomena called as the whole-body resonance; the electric power absorbed by the human body (and hence the SAR) will in this case increase markedly. Particularly in cases where the individual is standing on the ground plane, the human body will behave like a resonant-length monopole antenna, and a large induced current will flow through his/her ankles. It is known that since this current circumvents bones (with low electric conductivities) and concentrates in muscles and skin (with high electric conductivities), the SAR in the latter parts becomes extremely large[10].

Although it is difficult to measure ankle SAR directly, the SAR can be derived from the induced current passing through the ankles. Therefore, the radio-radiation protection guidelines stipulate additional guideline values in terms of the ankle-induced current and recommend that at any time there is a possibility that excessive ankle SAR will be gen-

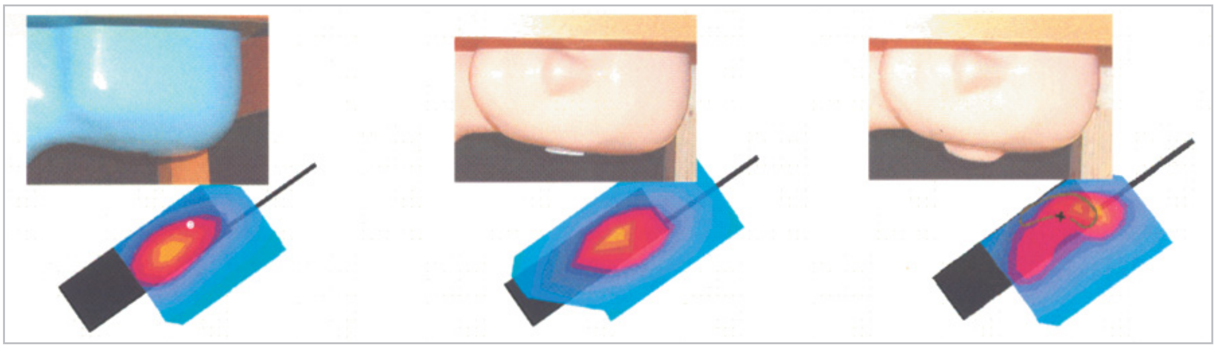

Fig. 1 *SAR distributions in the head phantoms*

European/American model (with loss-less ear pinna; left), Japanese model – (A) (with loss-less ear pinna; center), Japanese model – (B) (with lossy ear pinna; right). Frequency: 900 MHz, Antenna: radiation power normalized to 1 W.

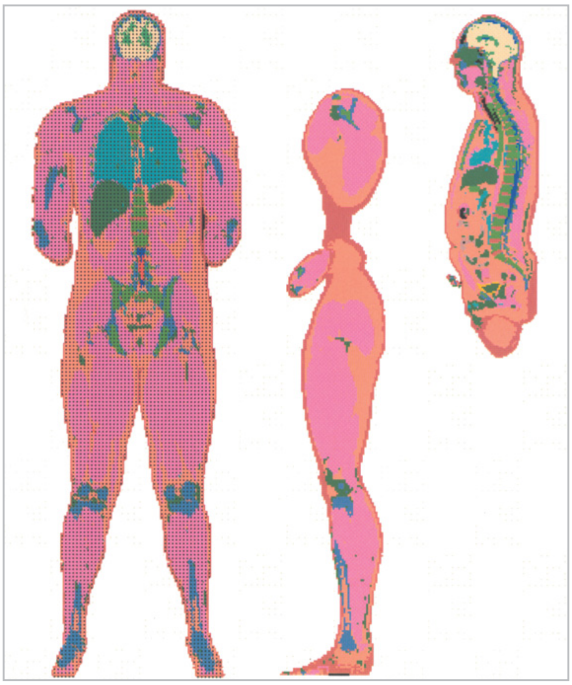

Fig.2 *Whole-body numerical model*

erated, the measured value of ankle-induced current be confirmed to be at or below the recommended guideline value.

However, since a technique for measuring ankle-induced current has not been sufficiently established (nor standardized), the guideline values are not included in the mandatory standards at the present moment. Thus, as a basic step in the process of establishing an ankle-induced current-measurement method, we have estimated ankle SARs under various grounding conditions by numerical simulation.

A whole-body numerical model used for the numerical simulation (FDTD (finite difference time domain) method[11]) is shown in Fig.2. This model has been developed from the database of the Visible Human Project in the United States.

In Fig.3, human-body vertical cross-section SAR distributions are shown for three cases: where the whole-body numerical model is made to (1) stand upright on a ground plane assumed to be a perfectly electrical conductor, (2) stand on its toes on this ground plane, (3) isolated from the ground plane, and (4) where the whole-body numerical model is in free space. It is shown that a different grounding area (standing upright versus standing on the toes) only minimally affects ankle SAR. It is also shown that, on the contrary, the ankle SAR changes significantly once the whole body numerical model is apart from the ground. When the distance “d” between the ground and the whole body model reaches 50 cm or more, the ankle SAR approaches that of SAR in free space.

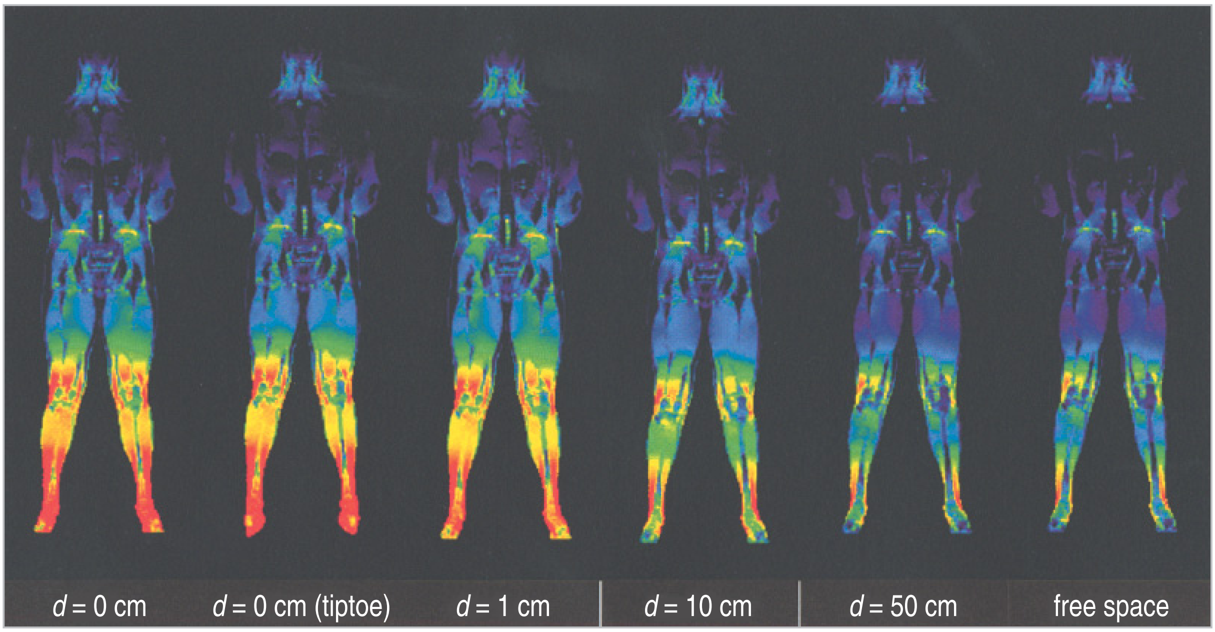

Fig.3 *Human-body vertical cross-section SAR distributions under various grounding conditions*

E-polarized plane wave is incident. Frequency: 40 MHz (near resonance frequency).

Presently, we are carrying out investigations into ankle SAR characteristics in cases where whole-body numerical models of various statures are assumed to be on the ground, with actual ground impedance values, as we develop a calibration method for the ankle-induced current meter and for a human-body-equivalent antenna.

In frequencies lower than those of the VHF band, we must consider the fact that nerves are directly stimulated by currents introduced into the human body. In particular, it is necessary to measure the contact current that can be used to counteract the stimulating action which occurs when the human body touches the surface of a metal body on which the high-frequency current is induced. In this context, we are currently measuring the contact impedance of the human body and developing a human-body-equivalent impedance circuit[12] as a basic step in the development of a contact-current meter.

3 Biological research[13][14]

When a cellular telephone is used, the power absorbed by the human body, or the SAR, concentrates in a local spot in the head, in close proximity to the antenna. However, since the total power absorbed by the head or by the whole body is extremely small, internal body temperature does not increase. In addition, due to the effect of the bloodstream and other factors, thermal energy diffuses rapidly from the local spot of the head where high SAR is generated, and even in this local spot, in close proximity to the antenna, the temperature increase is negligible[15]. Therefore, to evaluate the biological effects of exposure to radio waves when portable telephones are used, it is necessary to develop an exposure setup that realizes such conditions of high SAR in local target tissue, but in non-thermal conditions.

3.1 Exposure setup

In *in vivo* studies, small animals are mainly used, such as rats and mice. However, it is difficult to achieve localized exposure conditions in these animals, due to their extremely small size relative to humans.

To conduct exposure tests that concentrate on target tissue of small laboratory animals, we developed exposure setups where a rat fixed in a plastic tube was placed in the near field of a resonant monopole antenna (Figs. 4-6). These setups have certain advantages: (1) localized exposure can be realized on various tissues by optimizing the configuration between the rat and the antenna; (2) a number of rats can be exposed to the radio wave simultaneously, using a single antenna; and (3) the immobilization stress of the rat can be mitigated by ventilating temperature-controlled air.

Fig.4 shows a setup for localized exposure on the liver of rats, which was used in the research into the relationship between localized electromagnetic exposure and liver cancer[16][17]. Fig.5 shows a setup for localized exposure on the brain of rats, which was designed for research into the effects of exposure on the blood-brain barrier and on learning and memory functions[18][19]. Fig.6 shows a setup for localized exposure on the brain of rats throughout their life, whereby a constant local SAR is maintained in the brain through regulation of radiation power in accordance with the growth of the rat. This setup has been developed for the research to evaluate the effect of exposure on the development of brain tumors, requiring exposure during the period of the animal’s life.

Since the resonant-length monopole antenna for the frequency band employed by cellular telephones is almost the same size as the animals, localized exposure is limited, even if the animal is placed in the near field. That is, even if the local SAR is intended to be set to a high value, the electric power absorbed by the entire body also increases, resulting in a internal-body temperature increase. Accordingly, it is difficult to obtain non-thermal exposure conditions. As a result, we are developing an exposure setup that will enable more localized exposure, through the use of a miniature antenna (Fig.7).

Additionally, we are developing animal exposure setups intended to evaluate the biological effects of pulse waves and millimeter waves, further to research relating to the biological effects of radio waves other than those associated with the cellular telephone (Fig.8).

Moreover, we are also developing an exposure setup for *in vitro* studies with respect to the mechanisms of the biological effects of radio waves[20].

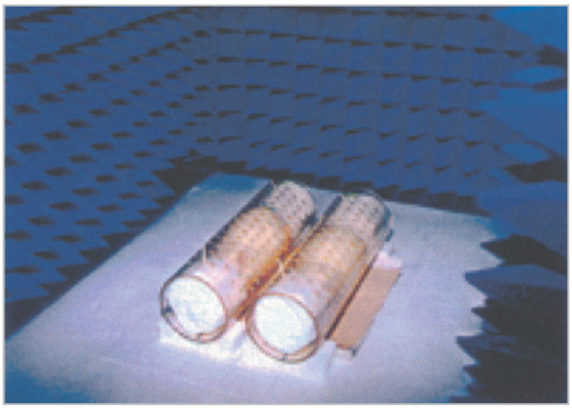

Fig.4 *Rat-liver localized exposure setup*

Resonant-length monopole antenna is used. Frequency: 900 MHz and 1,500 MHz.

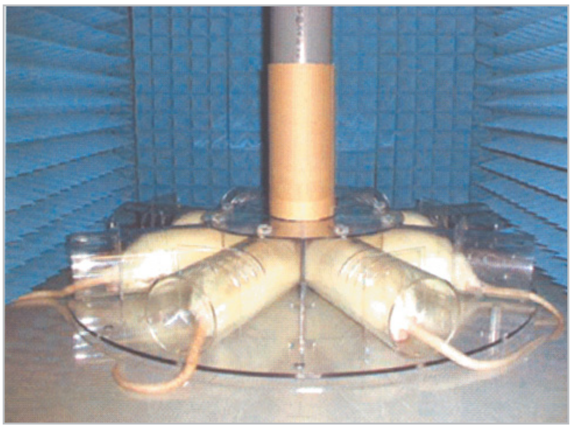

Fig.5 *Rat-brain localized exposure setup*

Resonant-length monopole antenna is used. Frequency: 1,500 MHz.

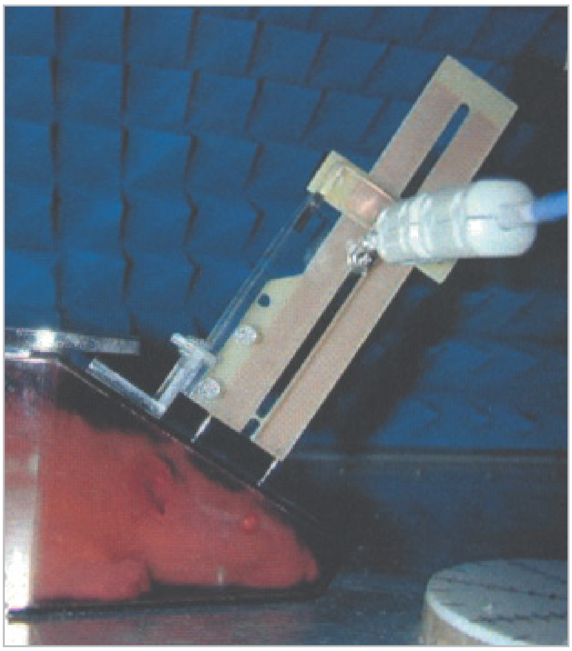

Fig.7 *Rat-brain exposure setup*

Miniature loop antenna is used. Frequency: 1,500 MHz.

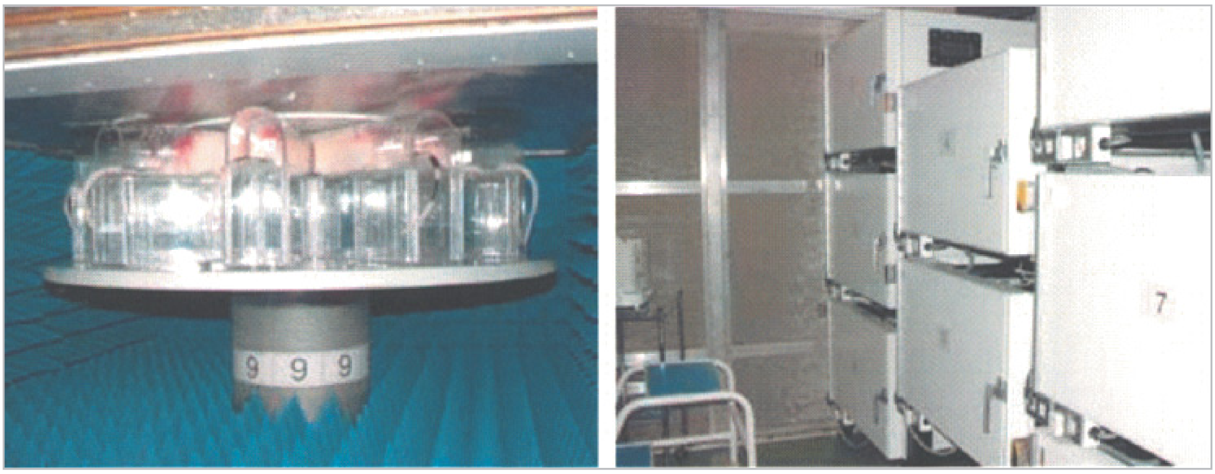

Fig.6 *Long-term large-scale rat-brain localized exposure setup*

Resonant-length monopole antenna is used. Frequency: 1,500 MHz.

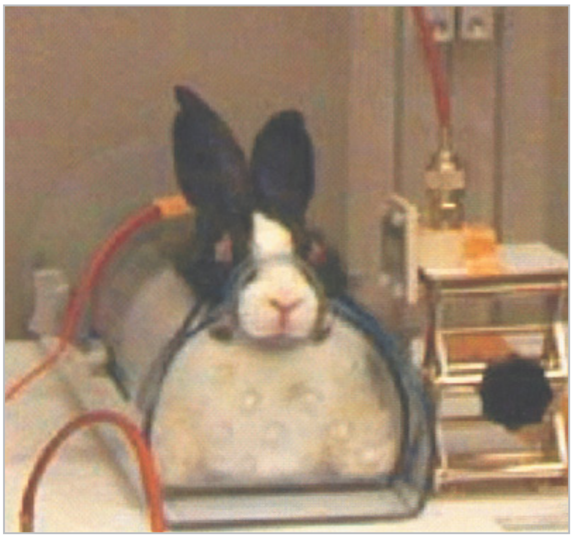

Fig.8 Pulse-wave exposure setup for rabbit-eye

Open-ended waveguide antenna is used. Frequency: 2,450 MHz.

3.2 Dosimetry

When localized exposure is realized on small animals with the near-field procedure described in the previous section, it is necessary to control the local SAR value of the target tissue accurately, by precisely adjusting the antenna input. It is thus critical to determine the relationship between antenna input and the SAR distribution with precision.

It is very difficult to measure the SAR distribution in an actual small animal accurately and with high resolution. One method involves measuring the SAR distribution by immobilizing the cadaver of the animal with paraffin or the like [21], but it is not always possible to conduct highly reproducible measurements in this manner, due to variations of the electric constant caused by effects of decomposition, damage to tissue resulting from insertion of the probe, and other factors. Therefore, we have built a numerical model with inhomogeneous internal tissue constructions based on anatomical charts and CT and MRI sectional image data, thereby permitting estimation of the SAR distribution in the animal with high precision via numerical simulation (the FDTD method) (Fig.9).

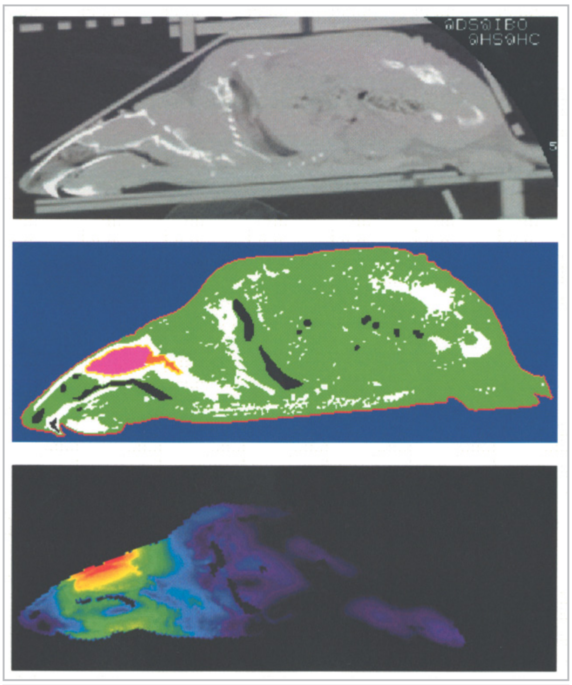

Fig.9 Rat CT image (upper), Numerical model (middle), and calculated SAR-distribution (lower)

Miniature loop antenna is used. Frequency: 1,500 MHz.

Accurate antenna modeling is not always achieved in the numerical simulation because of relatively coarse mesh of the simulated region, and hence it is recommended to confirm experimentally whether or not the numerical model is capable of accurately calculating the effects of mutual coupling between the antenna and the small animal placed in close proximity to the antenna. Therefore, the validity of the numerical simulation was experimentally confirmed through the following steps: (1) a solid phantom (homogeneous medium) having the same shape as the numerical model was constructed; (2) antenna input characteristics and the SAR distribution in the solid phantom when placed in the actual exposure setup were measured; and (3) the measurement results were compared with the calculation results (Fig.10).

Many of the exposure setups that were introduced in this section are currently being used in animal experiments organized by the Committee to Promote Research on the Possible Biological Effects of EMF, within the Ministry of Public Management, Home Affairs, Posts and Telecommunications. The contents of these animal experiments were

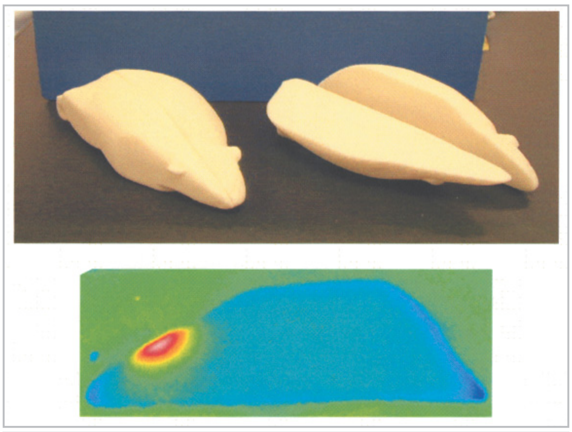

Fig.10 Solid-rat phantom (upper). Measured SAR-distribution (lower)

Miniature loop antenna is used. Frequency: 1,500 MHz.

summarized in the interim committee report^2.

4 Development of phantoms

In the dosimetry for the evaluation of the compatibility with standards and in the dosimetry for the exposure setups, phantoms with electric characteristics equivalent to those of the living body are used. In the numerical simulation, a numerical phantom is used to simulate the human body, including its detailed internal structure; in the experiment, on the other hand, a physical phantom constructed with a homogeneous medium is used. To perform high-precision dosimetry, it is essential to use an appropriate phantom. In this section, we will describe an outline of the human phantoms we are now developing. The dosimetry of the experimental animals was described in section 3.2.

4.1 Numerical phantom

A number of head models designed to calculate head SAR when a cellular telephone is used have been developed. In particular, models imitating the construction of internal tissue, based on MRI image data, have recently been developed [22][23]. On the other hand, we believe that a simulation will be required that uses a numerical model to represent the entire human body, in order to evaluate potential situations where radio waves from wireless communication terminals (such as a wearable wireless telecommunication terminal expected to be popular in near future) irradiate various part of the body other than the head, and not just the immediate area of the head. However, with respect to the whole-body model, as the areas of tissue identification are enormous, to date only a few models have been developed [24]. In particular, a whole-body model based on MRI data from Japanese subjects had yet to be produced; thus, we recently began to develop whole-body numerical models based on the average dimensions of the Japanese (Fig.11).

This model has a spatial resolution of 2 mm, and is composed of over 50 kinds of tissues. A preliminary example of a numerical simulation using this model is shown in Fig.12. It is expected that detailed dosimetry under a variety of conditions will become possible through the use of this model.

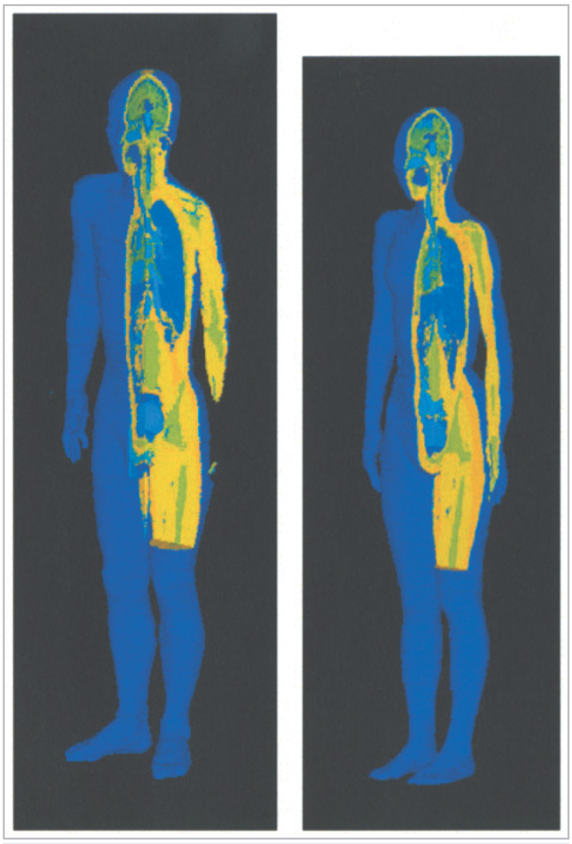

Fig.11 Japanese whole-body numerical models. Adult male model (left) and adult female model (right)

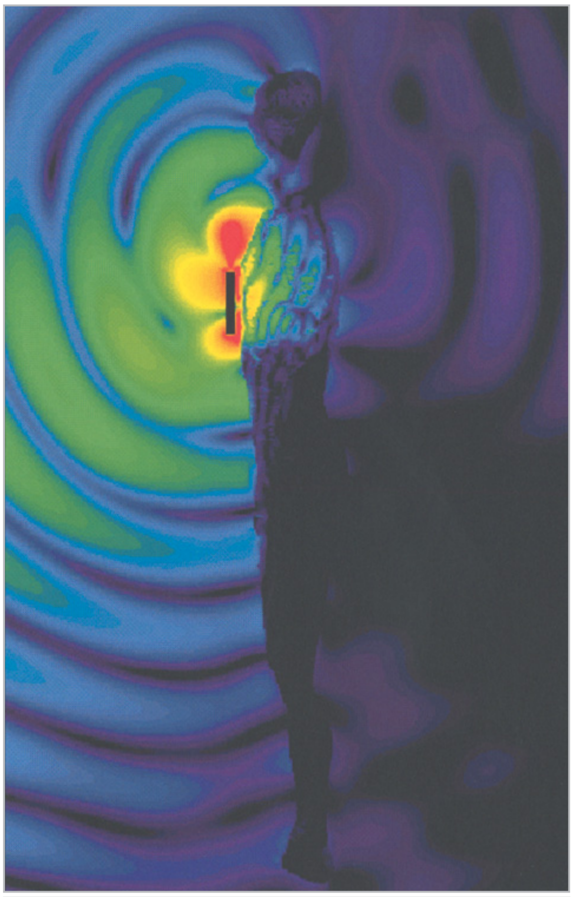

Fig. 12 Electric-field-strength distribution in the space including the Japanese whole-body numerical model (male) radiated from a cellular telephone in front of the chest. Frequency: 900 MHz.

4.2 Physical phantom

A phantom made of a solid material exhibits a temperature increase when irradiated by a high-strength electromagnetic field. If variations in temperature due to heat conduction are negligible, the SAR value can be derived from this temperature increase. This technique is used for the dosimetry of the small-laboratory animal phantom whose SAR cannot be measured with sufficient spatial resolution using the electric-field probe. We have, thus far, made advances in the investigation of more precise methods of SAR evaluation based on temperature measurements using an infrared camera [25].

For liquid phantoms used to measure the local SAR, deionized water has been used as the base material [4]. However, since the electric characteristics of water will vary due to evaporation, it is required that a liquid material with excellent long-term stability must be developed. At present we are pursuing the development of a phantom liquid material with excellent stability that can also be manufactured easily, in addition to developing a measuring method to determine the electric constant of liquids.

5 Summary

In accordance with the growing concerns of the general public regarding the effects of radio waves upon human health, the Electromagnetic Compatibility Group has continued to pursue research initiated in 1997 on the biological electromagnetic environment. This research is divided broadly between standards and measurement methods and biological studies. This text described the basic outlines of these research subjects.

For research related to standards and measurement methods, the effects of the head-phantom dimensions in measuring the head SAR when using the cellular telephone are evaluated, as are ankle SAR characteristics under various grounding conditions. In the biological experiments, experimental exposure setups are optimized for various biological studies, along with detailed dosimetry for the laboratory animals. For all of these research subjects, high-precision dosimetry is required, and to this end, the development of high-precision phantoms is underway.

It is hoped that these research results will contribute to the construction of a proper evaluation system for protection guidelines as well as to a more reliable groundwork for revising such guidelines, so that proper and safe radio wave environment may be realized.

[1] A phantom represents an experimental or numerical proxy, and here indicates a model simulating the electrical characteristics of human head tissues.

[2] http://www.soumu.go.jp/joho_tsusin/pressrelease/japanese/sogo_tsusin/010130_2.html

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***Soichi WATANABE**, Ph. D.*

Senior Researcher, Electromagnetic Compatibility Group, Yokosuka Radio Communications Research Center

Biological Effects of RF Exposure, Dosimetry

***Kanako WAKE**, Ph. D.*

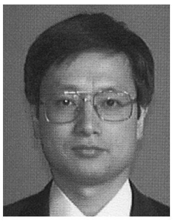
Researcher, Electromagnetic Compatibility Group, Yokosuka Radio Communications Research Center

Biological Effects of RF Exposure, Dosimetry

***Kaori FUKUNAGA**, Ph. D.*

Senior Researcher, Electromagnetic Compatibility Group, Yokosuka Radio Communications Research Center

Biological Effects of RF Exposure, Dosimetry, EMC Material



Yukio YAMANAKA

Leader, Electromagnetic Compatibility Group, Yokosuka Radio Communications Research Center

EMC