

PAPER

Realizing Highly Localized Exposure in Small Animals with Absorbing Material Covered Holder to Test Biological Effects of 1.5 GHz Cellular Telephones

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SUMMARY In testing the possible biological effects of electromagnetic exposure from cellular telephones in small animals such as mice, it is essential to realize a highly localized head exposure as close as possible to that due to cellular telephones in humans. In this study, a 1.5 GHz exposure setup was developed which has a highly localized specific absorption rate (SAR) of 2 W/kg in the mouse brain and a low whole-body averaged SAR of 0.27 W/kg. The low whole-body averaged SAR was realized by using a flexible magnetic sheet attachment on the mouse holder. Its validity has been carefully examined by both numerical simulation with an anatomically based mouse model and experimental simulation with a solid mouse phantom. Good agreement was obtained between the numerical and experimental results, which confirmed the effectiveness of the magnetic sheet attachment to the mouse holder.

key words: bio-electromagnetic environment, cellular telephone, animal experiment, exposure setup, absorbing material

1. Introduction

The recent rapid and ever more widespread use of cellular telephones has attracted public concerns regarding possible biological effects. The biological effects due to radio waves result mainly from a rise in temperature in tissues. A thermal threshold of whole body exposure was found at a whole-body-averaged specific absorption rate (SAR) of 4–8 W/kg from animal experiments, and therefore an average SAR below 0.4 W/kg should not be hazardous to human health. In contrast to the wealth of data available on whole body exposure, little is known about the possible biological effects of localized exposure due to near fields. The World Health Organization (WHO) recently recommended further scientific studies, especially *in vivo* animal experiments and epidemiological investigations for the near field exposure from cellular telephones [1].

Our group therefore conducted an animal experiment using Big Blue mice to investigate possible mutations in the brain due to electromagnetic (EM) fields from 1.5 GHz digital cellular telephones [2]. The goal of this study from an engineering standpoint was to realize a highly localized head exposure in the mouse that

is as close as possible to the cellular telephone exposure actually occurring in a human head. It is known that the ratio of the one-gram averaged peak SAR in the brain to the average SAR in the whole head is as high as about 20 for a portable telephone user [3]. To simulate such a situation in a mouse, the absorption power should be highly concentrated in the head, especially in the brain, while the whole-body averaged absorption power should be low enough not to cause any thermal stress. Since the safety guidelines applicable to cellular telephones in Japan limit a localized SAR to not exceed 2 W/kg averaged over any ten grams of tissue [4], our design goal for the exposure system was decided to realize (a) an average SAR above 2 W/kg in the animal brain, and (b) an average SAR below 0.4 W/kg in the whole body, which would be unlikely to cause any thermal stress in the animals. In other words, the ratio of the average SAR in the brain to the average SAR in the whole body should be larger than 5 at least.

Many *in vivo* exposure setups have been developed to test the biological effects of cellular telephones [5]–[10], but most of them were designed for rats with a size much bigger than mice. Figure 1 reviews the relationships between the average SAR in the brain and the average SAR in the whole body for some *in vivo* exposure

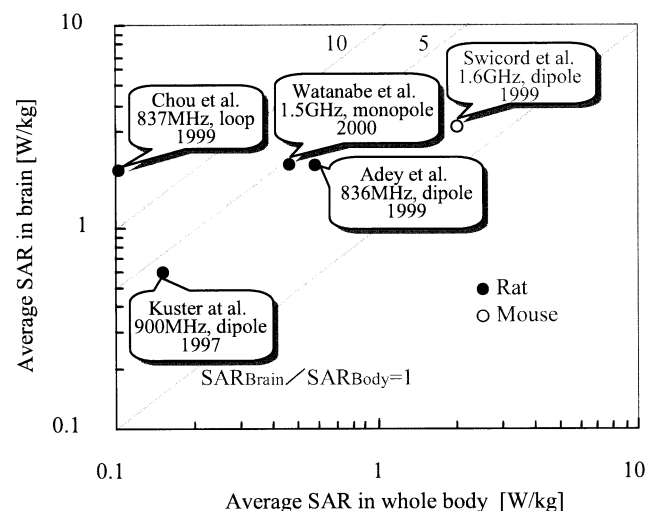


Fig. 1 Review of performances of localized exposure setups.

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setups as reported recently. Chou et al. used a small loop antenna, while the others used a half-wavelength dipole or a quarter-wavelength monopole antenna. The employment of the small loop antenna makes the ratio of the average SAR in the brain to that in the whole body larger than 20, but its power efficiency is poor [8]. Except for the small loop antenna, the ratio of the average SAR in the brain to that in the whole body was found to be smaller than 5 for rats and 3 for mice. These results imply the difficulty in realizing a localized exposure in a mouse with a small size. A direct application of these exposure setups to mice results in a whole body exposure, which may cause a redundant thermal stress.

The authors previously developed an *in-vivo* setup for localized exposure of the mouse dorsum with a short monopole antenna [11]. In this study, due to our limited budget for conducting the project, the basic structure of the above setup was assumed to realize a localized exposure in the mouse brain. For this aim, an absorbing technique was employed to reduce the whole-body averaged SAR in the mouse. This technique was based on the following consideration. In general, the mouse to be exposed should be constrained with an acrylic holder to keep it in the vicinity of the antenna to maintain a fixed exposure level. By covering the acrylic holder except for the head part with EM wave absorbing materials, a highly localized head exposure with a low whole-body averaged SAR would be achieved. Accordingly, a 1.5 GHz prototype exposure setup was designed, and a detailed numerical analysis of dosimetry, with an anatomically based mouse model, was made to demonstrate its validity. The results were also confirmed through phantom experiments.

2. Design of Antenna and Absorber-Covered Holder

The finite-difference time-domain (FDTD) method, together with an anatomically based mouse model, was employed in the design of the antenna and absorber-covered holder for a 1.5 GHz exposure setup. Figure 2 shows a simplified structure for the initial design. The mouse model was derived by scaling down a magnetic resonance image based Sprague Dawley rat model from Brooks Air Force Base, USA [12]. This yields a mouse-size model with a voxel size of $1.2 \times 1.2 \times 1.2$ mm and 20 tissue types. Some modifications were also made to simulate a more realistic shape for modeling a mouse inside a holder. The mouse model was placed in an acrylic holder with an inside diameter of 25 mm, a thickness of 5 mm and a length of 100 mm. A 6 mm wide slit was formed on the top of the upper half of the holder so that the mouse was just 3.6 mm beneath a monopole antenna which was fed through a metal plate. The dielectric properties of the mouse model were cited from Gabriel's data [13]. In the FDTD calculation, the

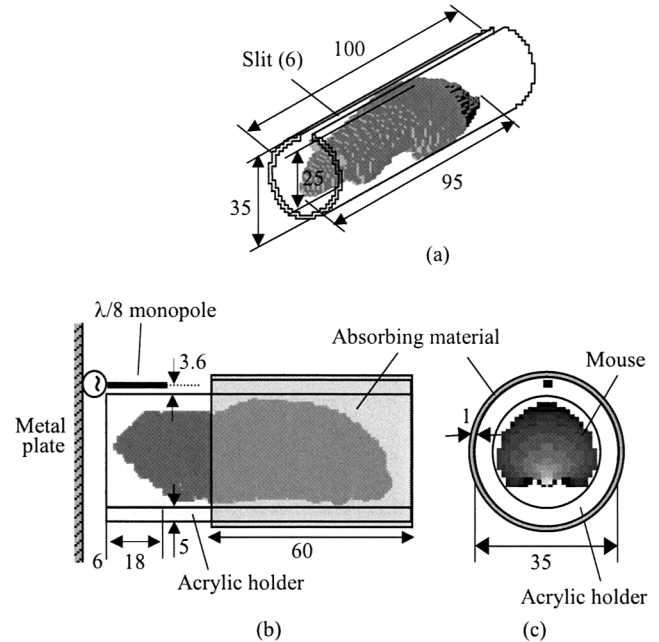


Fig. 2 Simplified exposure structure of mouse for preliminary design (unit:mm). (a) Mouse model in an acrylic holder, (b) side view and (c) back view of exposure setup.

Table 1 Effect of antenna length on SAR [W/kg].

	$\lambda/8$	$3\lambda/16$	$\lambda/4$
Average SAR in brain	2.0	2.0	2.0
Average SAR in whole body	0.57	0.74	0.89
Ratio of average SAR in brain to that in whole body	3.5	2.7	2.2
Antenna output [mW]	75.1	115.5	153.6

Frequency: 1.5 GHz

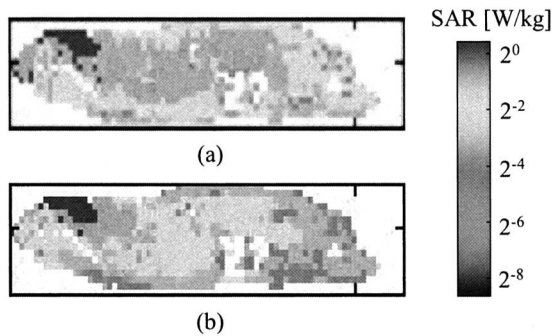
monopole antenna and its ground were simulated with perfect conductors, and the acrylic holder was simulated with its corresponding permittivity ($\epsilon_r=3.0$). The whole computation domain enclosing the antenna and mouse model was constructed with cubic cells with a size of 1.2 mm. The antenna element had a radius of 0.4 mm and was modeled using a thin-wire approximation. The antenna was excited by specifying a sinusoidal voltage across a one-cell gap. Twelve perfectly matched layers were employed in the boundaries to absorb outgoing scattered waves.

The length of the monopole antenna was first changed to investigate its effect on SAR distribution. Table 1 summarizes the effect of antenna length on the SAR distribution, which shows that the shorter the monopole is, the larger the ratio of the average SAR in the brain to that in the whole body becomes. For the $\lambda/8$ monopole, however, an antenna output of 75.1 mW yielded an average SAR of 2 W/kg in the brain with an average SAR of 0.57 W/kg in the whole body, and therefore the ratio of the SAR in the brain to that in the whole body was only 3.5 to 1.

A commercially available lossy dielectric sheet or

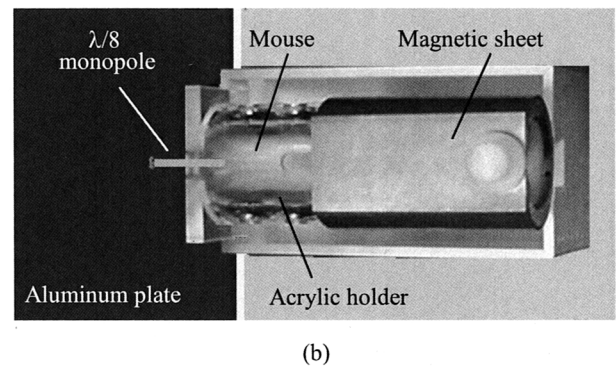
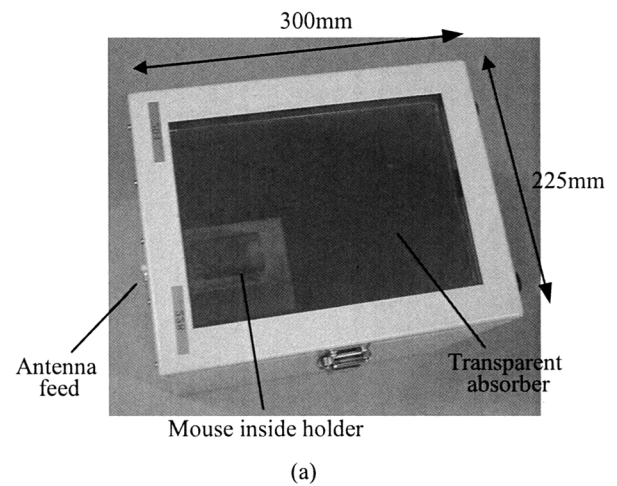
Table 2 FDTD-calculated SARs [W/kg].

	Without absorber	Dielectric sheet	Magnetic sheet
Average SAR in brain	2.0	2.0	2.0
Average SAR in whole body	0.57	0.52	0.28
Ratio of average SAR in brain to that in whole body	3.5	3.9	7.1
Antenna output [mW]	75.1	73.4	56.9

Antenna: $\lambda/8$ monopole; Frequency: 1.5 GHz**Fig. 3** Computed SAR distributions in a sagittal plane of mouse. (a) Without magnetic sheet attachment and (b) with magnetic sheet attachment. The antenna output was 56.9 mW and the frequency was 1.5 GHz.

magnetic sheet, with a thickness of 1 mm, was then attached to the part of the acrylic holder corresponding to the lower half of mouse, which was expected to act as an absorber so as to reduce the total EM absorption in the mouse. The complex relative permittivity and permeability were $20-j20$ and $1-j0$, respectively for the dielectric sheet, and $250-j10$ and $5.6-j6.25$, respectively for the magnetic sheet. With the adoption of a 1.2 mm cell size, the dielectric or magnetic sheet was modeled approximately with one cell. In the boundary between the absorbing sheet and the air or between the absorbing sheet and the acrylic, the averaged values both for the complex permittivity and the complex permeability were employed. Table 2 gives calculated SAR values in the mouse brain and whole body for the $\lambda/8$ monopole. Due to the attachment of the absorbing material, the ratios of the average SARs in the brain to those in the whole body were improved. In comparison with the dielectric material, the flexible magnetic sheet exhibited a more significant absorbing performance in reducing the SAR in the lower half of the mouse. In this case from Table 2, the whole-body averaged SAR was 0.28 W/kg for an average SAR of 2 W/kg in the brain, so that a ratio of 7.1 was achieved.

Figure 3 shows the SAR spatial distributions in a sagittal plane without and with the magnetic sheet attachment. As expected, with the magnetic sheet attachment, a high SAR area was realized in the mouse head, and the SAR in the lower half of the mouse was reduced.

**Fig. 4** Exposure box and magnetic sheet covered holder.

3. Dosimetry Evaluation

3.1 Exposure Setup

Based on the above preliminary investigation, a 1.5 GHz prototype exposure setup was developed as shown in Fig. 4. The exposure box of the setup was made of aluminum, and its inside, except for the left-side face and roof, were inlaid with a planar rubber ferrite absorber having a thickness of 7 mm and a reflection loss of at least 22 dB at 1.5 GHz. The roof of the box was made of a new-type transparent absorber (developed by TDK Corporation) with a thickness of 22.5 mm and was able to supply a reflection loss of 20 dB. The employment of the transparent absorber allowed real-time observation of the exposure process as well as the

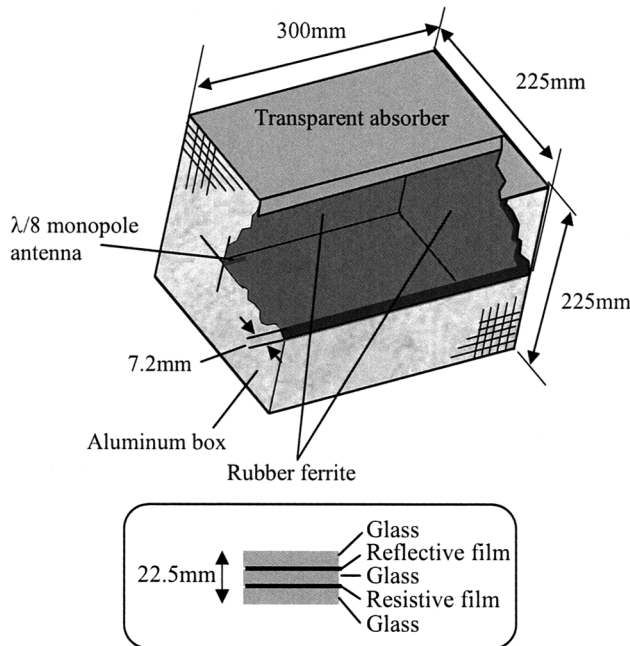


Fig. 5 Numerical model of exposure box with a cell size of 1.2 mm.

mouse activities. The left-side face of the box acted as the ground of a $\lambda/8$ -long monopole antenna with a horizontal arrangement. To obtain a high ratio of the average SAR in the brain to the average SAR in the whole body, a flexible magnetic sheet with a thickness of 1 mm was attached to the lower part of the acrylic holder, as shown in Fig. 4(b).

3.2 Numerical Evaluation

A dosimetry evaluation for the exposure setup developed was conducted numerically with the FDTD method. Figure 5 shows the numerical model of the exposure box, which was also constructed using $1.2 \times 1.2 \times 1.2$ mm cubic cells. The aluminum box and the monopole antenna were simulated with perfect conductors. Others such as the acrylic holder and rubber ferrite were simulated with their corresponding complex permittivity and permeability values as given in the previous chapter. The 7-mm thick rubber ferrite in-laid on the box walls was modeled approximately with 6 cells. The 22.5-mm thick transparent absorber was composed of five layers, i.e., glass, resistive film, glass, reflective film, and glass, as shown in Fig. 5. The surface resistivities were $528 \Omega/\square$ for the resistive film and $15 \Omega/\square$ for the reflective film, which were modeled in the FDTD analysis with an infinitely-thin surface having a conductivity σ that can be given by $\sigma = 1/R_s\delta$ where R_s is the surface resistivity value and δ is the cell size [14].

The numerical results for the SAR in the actual exposure environment are tabulated in Table 3 and

Table 3 FDTD-calculated SARs [W/kg] in actual exposure box.

Average SAR in brain	2.0
Average SAR in whole body	0.27
Ratio of average SAR in brain to that in whole body	7.4
Antenna output [mW]	55.1
Antenna: $\lambda/8$ monopole	
Frequency: 1.5 GHz	

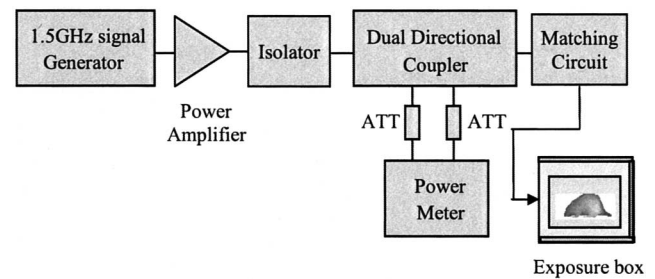


Fig. 6 Setup for experimental evaluation of mouse dosimetry.

show that, with the attachment of the flexible magnetic sheet, the whole-body averaged SAR was 0.27 W/kg for an average SAR of 2 W/kg in the mouse brain. A ratio of 7.4 of the average SAR in the brain to that in the whole body was achieved, when the required antenna output was 55.1 mW. The results were almost identical to the preliminary ones in the previous chapter.

3.3 Experimental Evaluation

The experimental evaluation was conducted with homogeneous solid (gel with agar added) phantoms which had a similar but not completely identical shape to the numerical mouse model for ease of manufacture. Their conductivity and relative permittivity were found to be 0.89 S/m and 54.46, respectively, using a network analyzer and a dielectric probe kit (HP8753A + HP85046A). Figure 6 shows a setup for experimental dosimetry evaluation. The antenna input power was approximately 60 W, and the mouse phantom was exposed for 30 seconds. The SAR in the mouse phantom was measured with two methods, which are described below.

In the first method an infrared image camera (Nippon Avionics, TVS-8100MKII) was employed. The mouse phantom before exposure was first set close to the ambient temperature, and the corresponding infrared image in a sagittal plane was recorded. After the 30-second exposure, the mouse phantom was immediately removed from the exposure box and the infrared image was obtained again. Then from the above image difference, the temperature rise at the phantom surface was obtained. Under the assumption of linear energy deposition within the 30-second period, the SAR was determined from

$$SAR = C_p \frac{\partial T}{\partial t} \cong C_p \frac{\Delta T}{\Delta t} \quad (1)$$

where C_p is the specific heat [J/kg·°C], ΔT is the temperature rise due to the exposure, and Δt is the exposure time. The value of C_p was taken to be 3770 J/kg·°C.

In the second method three fluoroptic temperature probes (Luxtron, Model SMM) were used in lieu of the infrared image camera. The temperature probes were inserted into the phantom and set at three locations along the mouse surface with 2.4-cm intervals and a 3-mm depth. The temperature reading at each location was recorded every 1/4 second over the 30-second period. Then the SAR at each location was determined in the same way as in the first method. The process was repeated three times, and in each measurement a new mouse phantom was used.

Figure 7 shows the infrared image after 30-second exposure with an antenna input of 60 W at 1.5 GHz. As expected, a localized exposure to the mouse brain was indeed realized.

Figure 8 shows SAR profiles along a horizontal line inside the mouse phantom with a depth of 3 mm from the upper surface. Also shown in the figures with a solid line is the SAR computed using the FDTD method in conjunction with the same homogeneous model. As

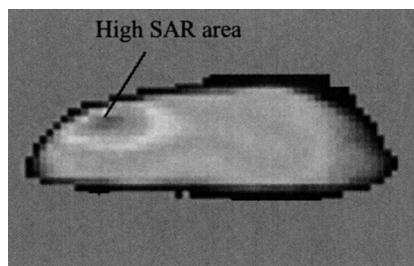


Fig. 7 Infrared image in a sagittal plane of mouse phantom.

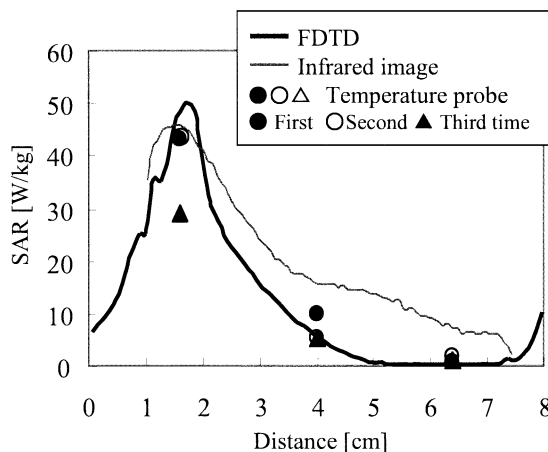


Fig. 8 SAR profile along a horizontal line inside the mouse phantom with a depth of 3 mm from the upper surface. The antenna input power was 60 W and the frequency was 1.5 GHz.

can be seen, both the infrared image method and the temperature probe method gave fair agreement with the FDTD computation. The total agreement among the two measurements and FDTD computation assured the reliability of the dosimetry analysis and the effectiveness of the magnetic sheet attachment in reducing the whole-body averaged SAR. Compared to the FDTD computation, the discrepancy at the head area in the third-time temperature probe measurement was considered to be due to a location error because setting the probe at an accurate depth was not easy, and the slightly higher SAR level for the infrared camera result at the lower half of the mouse phantom was due to the diffusion of heat from high to low SAR areas during the period of time needed to remove the mouse phantom to the outside of the exposure box in order to take the image.

4. Conclusion

A setup that enables higher local exposure in a mouse brain while whole-body averaged SAR is low has been developed. The low whole-body averaged SAR was realized by using a flexible magnetic sheet attachment on the mouse holder. As a result, a ratio of 7.4 of the average SAR in the brain to that in the whole body was achieved. The validity was confirmed through numerical simulation with an anatomically based mouse model and experimental simulations with solid mouse phantoms.

Further issues are to optimize the properties of the absorbing material and improve the power efficiency of the exposure antenna, as it is electrically short in terms of the wavelength in the present version.

Acknowledgment

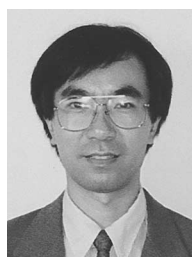
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