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Variability of Specific Absorption Rate of Human Body for Various Configurations of Tablet Computer in Vicinity of Abdomen

Akihiro TATENO[†a)], ***Student Member***, **Tomoaki NAGAOKA**[††], **Kazuyuki SAITO**[†††], **Soichi WATANABE**[††], ***Members***, **Masaharu TAKAHASHI**[†††], ***and*** **Koichi ITO**[†††], ***Fellows***

SUMMARY With the development and diverse use of wireless radio terminals, it is necessary to estimate the specific absorption rate (SAR) of the human body from such devices under various exposure situations. In particular, tablet computers may be used for a long time while placed near the abdomen. There has been insufficient evaluation of the SAR for the human body from tablet computers. Therefore, we investigated the SAR of various configurations of a commercial tablet computer using a numerical model with the anatomical structures of Japanese males and females, respectively. We find that the 10-g-averaged SAR of the tablet computer is strongly altered by the tablet's orientation, i.e., from −7.3 dB to −22.6 dB. When the tablet computer is moved parallel to the height direction, the relative standard deviations of the 10-g averaged SAR for the male and female models are within 40%. In addition, those for the different tilts of the computer are within 20%. The fluctuations of the 10-g-averaged SAR for the seated human models are within ±1.5 dB in all cases.

key words: *specific absorption rate (SAR), wireless radio terminals, numerical models of human, finite-difference time-domain (FDTD) method*

1. Introduction

Since wireless radio terminals have become indispensable in our daily lives, the number of situations wherein one is exposed to electromagnetic (EM) waves from such devices has been increasing. Therefore, there is increasing public interest in the health risk associated with exposure to EM waves. When the human body absorbs EM energy in the high-frequency band (above 100 kHz), thermal effects occur in human tissue. The specific absorption rate (SAR) has been adopted as the standard parameter for radio-frequency (RF) exposure [1], [2]. For local exposure from antennas, SAR_{10g}, which is obtained by averaging the SAR over a mass of 10 g, is often evaluated and compared with the safety guidelines [1], [2]. In light of the difficulty of evaluating SAR_{10g} for an actual human body by measurement owing to ethical issues, the SAR_{10g} for the human body has been estimated by calculation using a numerical model of the human body.

Conventionally, mobile phones with a 2nd-generation (2G) wireless communication system are used close to the human head during calling. Therefore, it is important to evaluate exposure levels for the human head. Previously, near-field exposures from wireless radio terminals are evaluated for the human head [3]–[6].

Recently, new types of wireless radio terminals such as smart phones and tablet computers with 3rd- and 4th-generation wireless communication systems have been spreading rapidly. The World Health Organization (WHO) announced that the RF exposure for the human body from new wireless radio terminals should be evaluated as a high-priority researches topic [7]. The new wireless radio terminals have diverse uses and are not always used in the vicinity of the head in different from conventional devices with the 2G wireless communication system. Therefore, we focused on tablet computers as the new wireless radio terminal in this study because there has been insufficient RF dosimetry for the human body exposed to EM waves from a tablet computer. Especially, tablet computers are used in various positions in the vicinity of the abdomen and in various orientations in contrast to conventional mobile phones. The position of the human body relative to the antenna of a tablet computer depends on how the computer is held. Therefore, the novelty of this study is the evaluation of the near-field exposure for the human abdomen due to various configurations of a tablet computer. The computer also has many kinds of antennas such as antennas for the 3rd-generation (3G) wireless communication system and the wireless fidelity (Wi-Fi) system.

Therefore, in this paper we present a study on the variability of the SAR_{10g} for a human body exposed to EM waves at 900 MHz and 2 GHz from a typical tablet computer placed in various positions, i.e., different directions, heights, and tilts of the terminal and different postures of the human, by numerical calculation using the finite-difference time-domain (FDTD) method.

2. Method and Models

2.1 Numerical Model of a Tablet Computer Model

In the reference [3]–[6], several realistic numerical models of the mobile phone are developed by the computer aided design (CAD) to actualize more practical case of using the mobile phone. The development of realistic wireless radio terminals is important because the RF exposure levels and situations may be different between simple and realistic ter-

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[†]The author is with the Graduate School of Engineering, Chiba University, Chiba-shi, 263-8522 Japan.
[††]The authors are with the Applied Electromagnetic Research Institute, National Institute of Information and Communications Technology, Koganei-shi, 184-8795 Japan.
[†††]The authors are with the Center for Frontier Medical Engineering, Chiba University, Chiba-shi, 263-8522 Japan.
a) E-mail: a.tateno@chiba-u.jp

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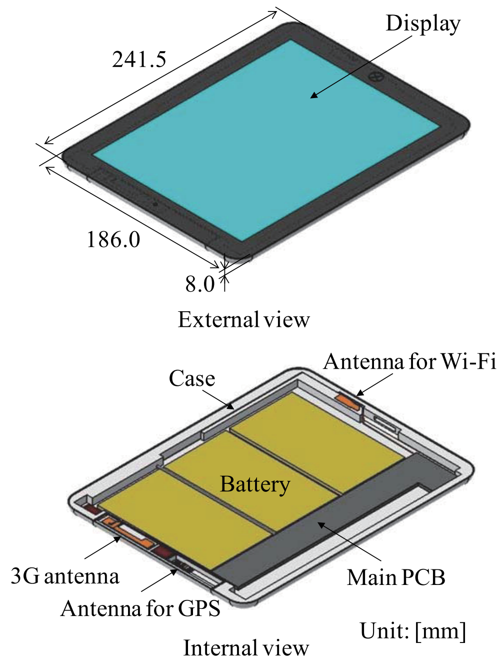

Fig. 1 Illustration of numerical model of a typical tablet computer.

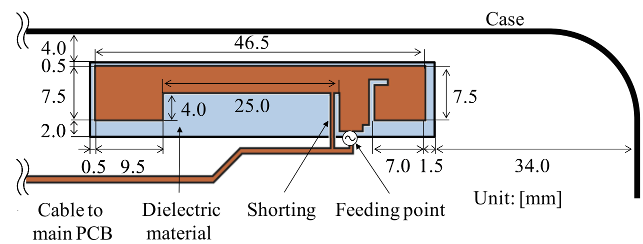

Fig. 2 Illustration of the structure of the 3G antenna.

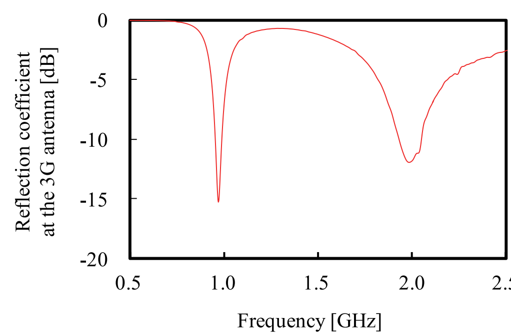

Fig. 3 Reflection coefficient of the 3G antenna.

minals. For the numerical calculations of the RF dosimetry for the human body, accurate numerical models of the human, e.g., based on the magnetic resonance image, have been available. Therefore, realistic wireless radio terminal models are also required as an approach to study the interaction between the human body and the wireless radio terminal.

In order to evaluate the SAR for the human body in actual situations of using a tablet computer, it is necessary to develop a realistic numerical model of a tablet computer. Figure 1 shows a high-resolution model of a typical tablet computer that we modeled in this study in reference to a commercial tablet computer used worldwide. The size is $186.0 \times 241.5 \times 8.0\,\mathrm{mm}^3$. The wireless communication methods of this tablet computer are the 3G communication system and Wi-Fi system. The antennas for the 3G wireless communication system, Wi-Fi, and global positioning system (GPS) are included in this computer. These antennas are connected to the main print circuit board (PCB) by a coaxial cable. There are three batteries with the size of $114.0 \times 63.0 \times 3.0\,\mathrm{mm}^3$. The case is made of a metallic material. The production process of the tablet computer model was as follows. First, an actual tablet computer was imaged by taking an X-ray photograph to determine the positions of the internal materials. Then, the computer was dismantled and the lengths of the components such as the antennas, PCBs, batteries, and other small parts were measured. Secondly, on the basis of the obtained data, we constructed a tablet computer model using the CAD. Finally, the CAD model was resolved for a voxel model and the electrical properties were set for each voxel. The PCBs, batteries, coaxial cables, case, and antenna elements were modeled as perfect electrical conductors. The display was modeled as a dielectric material with $\varepsilon_r = 5.0$ and $\sigma = 0.0$.

In this study, we only consider the 3G antenna because it had the highest radiation power in the three antennas. Figure 2 shows the structure of the 3G antenna. The electrical properties of a dielectric material on the antenna element are $\varepsilon_r = 3.0$ and $\sigma = 0.0$. The 3G antenna was a planar inverted-F antenna because the radiated plate was connected to the cable by the feeding and shorting. The minimum cell size of the tablet computer model was $0.5 \times 0.5 \times 0.5\,\mathrm{mm}^3$ around the 3G antenna. The maximum cell size was $1.0 \times 1.0 \times 1.0\,\mathrm{mm}^3$. Thus, the cells in the model were non uniform and had dimensions varying from 0.5 to 1.0 mm.

2.2 Validation of the Numerical Model of the Tablet Computer

Figure 3 shows the reflection coefficient at the 3G antenna when the tablet computer model was placed in free space. The reflection coefficient was calculated by XFdtd ver. 7 [8], which is commercial software for FDTD analysis. The operating frequencies of the 3G antenna were 900 MHz and 2 GHz. In Fig. 3, we confirmed that the antenna resonates at these frequencies.

We compared the SAR distributions in a flat phantom with the tablet computer between the numerical calculation and the experimental measurement.

In this study, the measurement results of the SAR distributions from the tablet computer were taken from [9]. Figure 4 shows the calculation model. A dielectric of 2.0 mm thickness was assumed as the bottle of the liquid phantom. The electrical properties of the liquid phantom at 900 MHz and 2 GHz are $\varepsilon_r = 54.6$, $\sigma = 1.0$ S/m and $\varepsilon_r = 51.9$, $\sigma = 1.5$ S/m, respectively. Those of the dielectric are

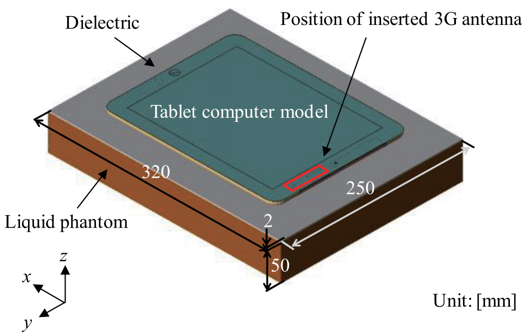

Fig. 4 Model used to calculate SAR distributions.

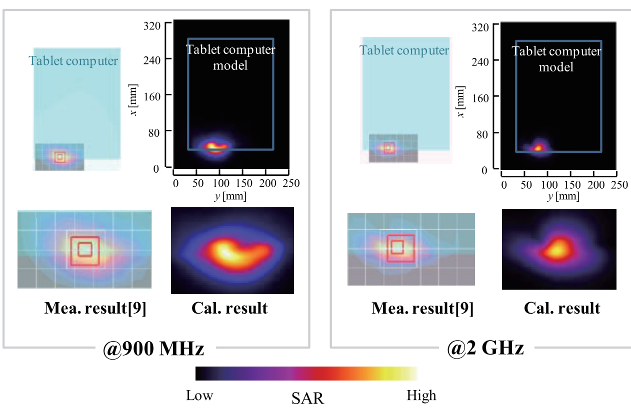

Fig. 5 Comparison of SAR distributions between calculations and measurements [9].

$\varepsilon_r = 4.5$, $\sigma = 0.0$ at both frequencies. The density of both the liquid phantom and dielectric is 1000 kg/m^3. The side opposite to the display is attached to the dielectric. The observation plane was 5 mm below the surface of the flat phantom. Figure 5 shows the calculated and measured SAR distributions. The measurement conditions were the same for the calculation conditions described above. We confirmed that the distributions were similar to each other at both frequencies.

2.3 Numerical Human Models

In this study, anatomically realistic whole-body voxel models of an adult Japanese male and female named TARO and HANAKO [10] with a $2.0 \times 2.0 \times 2.0$ mm^3 voxel grid were employed. The models consist of 51 different tissue types. The body height and weight of the human models corresponded to the averaged values for a Japanese male and female. The electrical properties and densities of the male and female models were taken from [11] and [12], respectively.

3. Results

3.1 SAR for the Human Models from the Tablet Computer at the Original Position

Figure 6 shows the original position of the tablet computer model, which was placed horizontally near the abdomen of the human models in free space. The feeding point of the antenna in the tablet computer model was the height of the navel to model the use of a tablet computer in proximity to an abdomen. The abdomen of the human models is not flat. Therefore, the distance from the edge of the tablet computer model to the surface of the human model was fixed at 10 mm as you can see in Fig. 6. The median line of each human model corresponded to the perpendicular bisector of the short side of the tablet computer model. The minimum cell size was $0.5 \times 0.5 \times 0.5$ mm^3 and the maximum cell size was $2.0 \times 2.0 \times 2.0$ mm^3 in both models. The boundaries of

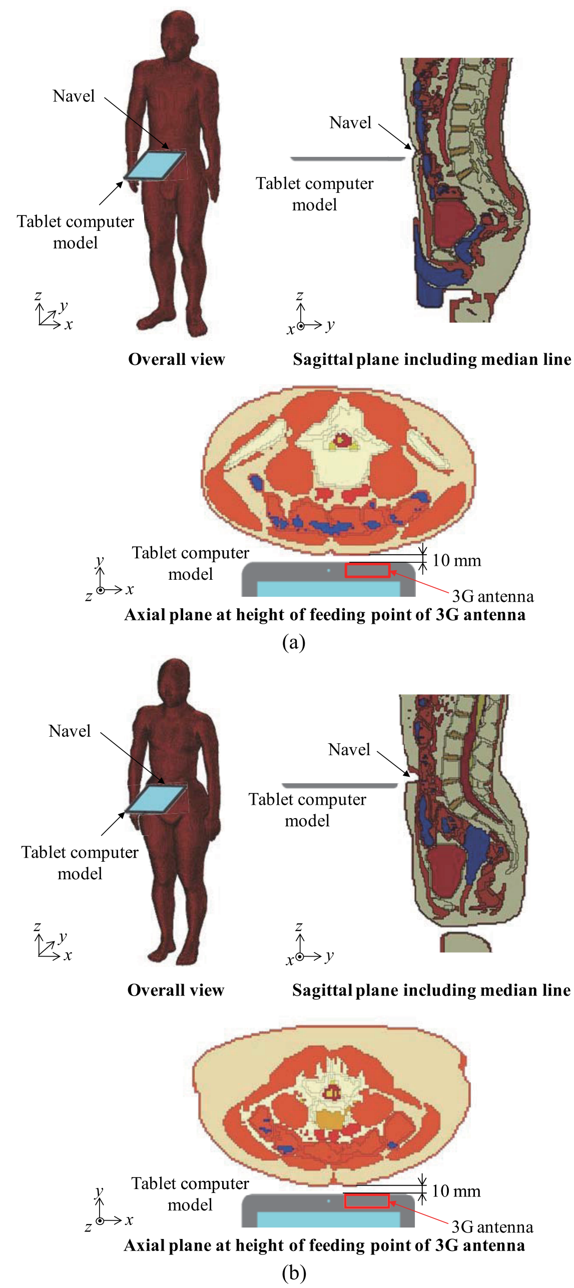

Fig. 6 Original position of the tablet computer model in the vicinity of the abdomen of (a) the male model and (b) the female model.

Table 1 Peak SAR_{10g} values from the tablet computer at the original position [W/kg].

	900 MHz	2 GHz
Male	0.27	1.12
Female	0.36	1.35

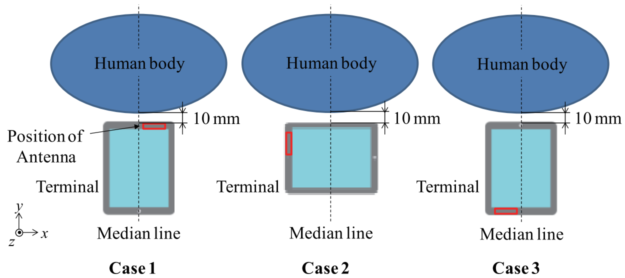

Fig. 7 Different directions of the tablet computer model.

the calculation region were formed using perfectly matched layer (PML) boundary conditions (eight layers). All calculations of the SAR_{10g} were performed by XFdtd ver. 7 [8].

In this study, as the worst-case evaluation, the radiation power was maintained at 0.25 W for both frequencies in consideration of the maximum power in the 3G wireless communication system [13]. Therefore, the mismatch loss when the antenna was placed in the vicinity of the human body was not considered.

Table 1 lists the peak SAR_{10g} values at the original position. The SAR_{10g} value at 2 GHz was approximately 4 times higher than that at 900 MHz for both human models. The SAR_{10g} values at both frequencies for the female model were approximately 1.3 times higher than those for the male model in this case.

3.2 Variability of the SAR Due to the Direction of the Tablet Computer Model

Tablet computers are generally held at arbitrary directions unlike with a mobile phone. To investigate the relationship between the SAR_{10g} of the human body and the direction of the tablet computer, we estimated the SAR_{10g} for the three directions shown in Fig. 7 (Case 1 to 3). The direction of the tablet computer model in Case 1 was the same that for the original position in the previous section. In Case 2, the computer was rotated 90° around the z-axis from the original position so that the median line of the human models corresponded to the perpendicular bisector of the long side. In the Case 3, the computer was rotated 180° around the z-axis from the original position. The cell size, the boundary conditions, and the calculation software were the same as those in the previous section.

Figure 8 shows the peak SAR_{10g} for the human models normalized by the value for Case 1, i.e., the value for the original position listed in Table 1. The peak SAR_{10g} for Case 1 is highest for both human models and at both frequencies. The maximum differences from peak SAR_{10g} values of Case

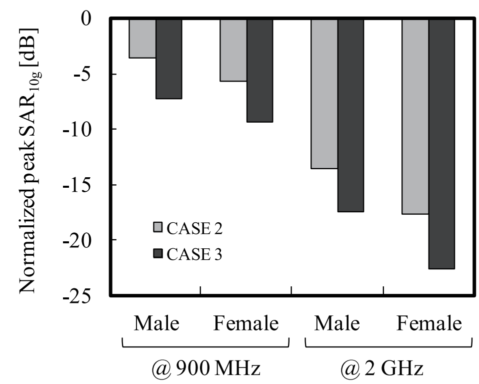

Fig. 8 Normalized peak SAR_{10g} for different directions of the tablet computer model.

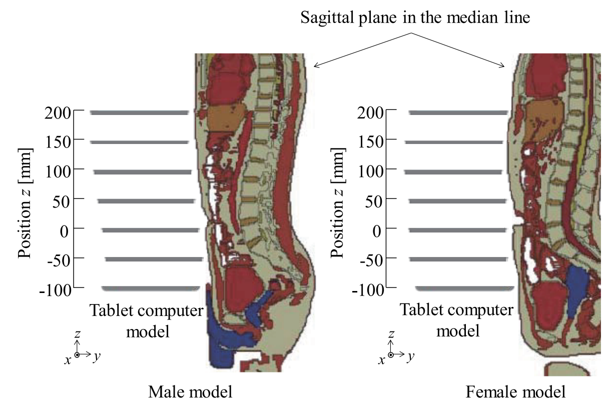

Fig. 9 Positions of the tablet computer model with movement parallel to the $\pm z$-axis for the male and female models.

1 at 900 MHz for the male and female are approximately −7.3 dB and −9.4 dB, respectively. At 2 GHz, those are approximately −17.4 dB and −22.6 dB. Also, the variability of SAR_{10g} at 2 GHz is larger than that at 900 MHz.

3.3 Variability of the SAR Due to the Height of the Tablet Computer Model

We evaluated the variability of the SAR_{10g} of the human body upon moving in the parallel direction along with z-axis. Figure 9 shows the different positions of the tablet computer model. The tablet computer model was moved in the steps of 50 mm from the original position while maintaining the distance of 10 mm from the surface of the human body. $z = 0$ corresponded to the original position. The cell size, the boundary conditions, and the calculation software were the same as those in the previous section.

Figure 10 shows the normalized peak SAR_{10g} for the male and female models at 900 MHz and 2 GHz when the tablet computer model was moved along the z-axis. The SAR_{10g} values are normalized by those of $z = 0$ mm, i.e., the original position. The variability of SAR_{10g} for the male model is larger than that for the female model. In particular, the SAR_{10g} values for the male model in the range of $100\,\text{mm} \leq z \leq 200\,\text{mm}$ at 900 MHz are approximately 3 dB

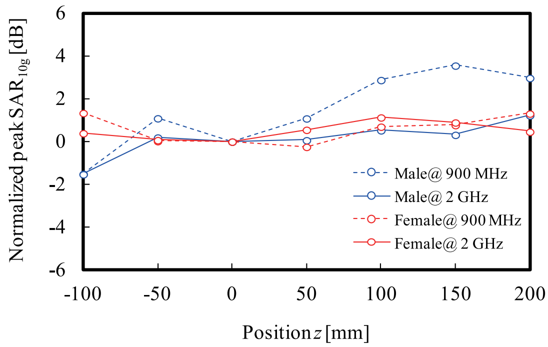

Fig. 10 Normalized peak SAR_{10g} for different heights of the tablet computer model.

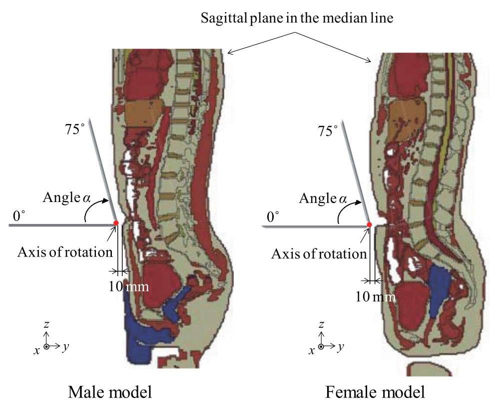

Fig. 11 Positions of the tablet computer model with rotation around the x-axis for the male and female models.

higher than that at $z = 0$. However, such increase is not shown for the male at 2 GHz and for the female at both frequencies.

3.4 Variability of the SAR Due to the Tilt of the Tablet Computer Model

We evaluated the variability of the SAR_{10g} with the tilt angle of the tablet computer model. Figure 11 illustrates the calculation model with the tablet computer model tilted in the step of 15° from the original position ($\alpha = 0°$) to $\alpha = 75°$. The axis of rotation was the x-axis corresponding to the short side of the tablet computer model nearest to the human models. The distance between the tablet computer model and the surface of each human model was maintained at 10 mm during the rotation. The cell size, the boundary conditions, and the calculation software were the same as before.

Figure 12 shows the normalized peak SAR_{10g} for the male and female models at 900 MHz and 2 GHz when the tablet computer model is tilted from $\alpha = 0°$ to $\alpha = 75°$. The values are normalized by those at the tilt angle of $\alpha = 0°$, i.e., the original position. As the tilt increases, the large variability of SAR_{10g} for the male model appears, while such large variability of SAR_{10g} does not appear for the female model. The maximum difference from SAR_{10g} value at $\alpha = 0°$ is approximately +2.4 dB for the male model at both frequencies.

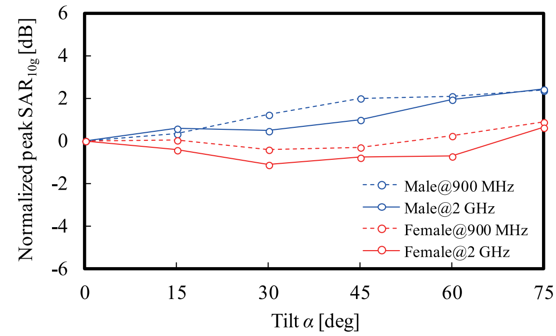

Fig. 12 Normalized peak SAR_{10g} for different tilts of the tablet computer model.

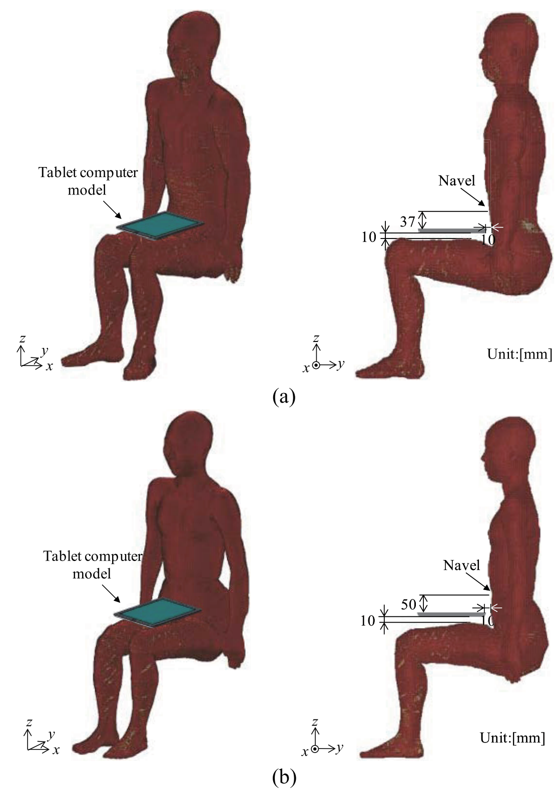

Fig. 13 Calculation models (a) seated male model and (b) seated female model.

3.5 Variability of the SAR Due to the Posture of the Human Models

We estimated SAR_{10g} for seated human models. Figure 13 illustrates the seated human models [14] used in the calculation. The distance from the tablet computer to the surface of the abdomen and legs was 10 mm in both cases. The tablet computer model was 37 mm and 50 mm below the height of the navel for the male model and the female model, respectively. The median line of human models corresponded to the perpendicular bisector of the short side of the tablet com-

Table 2 Normalized peak SAR_{10g} for seated human models [dB].

	900 MHz	2 GHz
Male	-1.5	1.1
Female	-1.1	0.2

puter model. The cell size, the boundary conditions, and the calculation software were the same as before calculations.

Table 2 lists SAR_{10g} for the seated human models. These values are normalized by the values at $z = -50$ mm for the stood models described in Sect. 3.3. As can be seen in Table 2, we confirmed that the variability of SAR_{10g} for the seated models was within ±1.5 dB in all cases.

4. Discussion

SAR_{10g} in a human exposed to EM waves from antennas of tablet computers may change with the configuration of the tablet computer or the posture of the human models. Therefore, as mentioned in the previous section, we evaluated the variability of SAR_{10g} when the direction, height, and tilt of the computer or the posture of the human models (standing or sitting) was changed.

In the case of the original position, the SAR_{10g} value was substantially higher at 2 GHz than at 900 MHz. This is mainly caused by the skin depth of the EM waves. In addition, the SAR_{10g} values at both frequencies for the female model were slightly higher than those for the male model in this case. Figure 14 shows the SAR distributions at 2 GHz at the axial plane including the feeding point of the 3G antenna. These distributions are normalized by the maximum SAR value of the female model. We found that the high SAR for the female model is distributed largely the skin at the navel. Thus, the differences of the surface shape and the structure in the front of the mid-abdomen caused the difference of the SAR_{10g} between the male and female models.

We found that the different directions of the tablet computer model sufficiently contribute to the variability of SAR_{10g} for the human body. This is because SAR_{10g} for the human body depends on the distance between the antenna and the surface of the human body. Also, the distances between the antenna and the human body in Cases 2 and 3 are 44 and 236.5 mm, respectively. The SAR_{10g} in a tissue at 900 MHz and 2 GHz decreases in dependence on the distance versus wavelength between the EM source and the tissue [15]. When the distance becomes larger in the same way at 900 MHz and 2 GHz, the decrease of the SAR_{10g} is larger at 2 GHz than at 900 MHz. Therefore, the variability of SAR_{10g} was larger at 2 GHz than at 900 MHz.

In terms of the variability of SAR_{10g} for the different heights in Sect. 3.3, the maximum difference from SAR_{10g} value at $z = 0$ is +3.6 dB in the male model at 900 MHz, whereas such difference does not appear for the male model at 2 GHz and the female model at both frequencies. This is because the EM wave at 900 MHz penetrates the human body more deeply than that at 2 GHz since the fat layer is

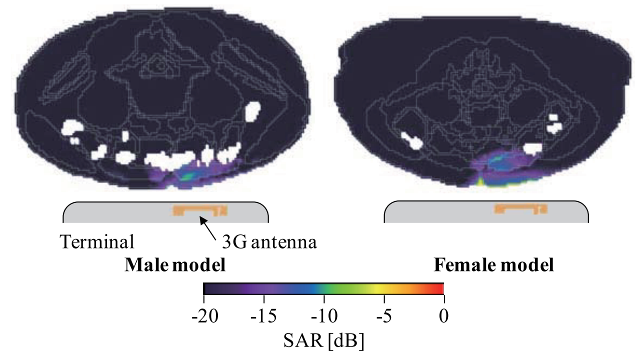

Fig. 14 Normalized SAR distributions at 2 GHz in the axial planes of the male and female models at the height of the feeding point.

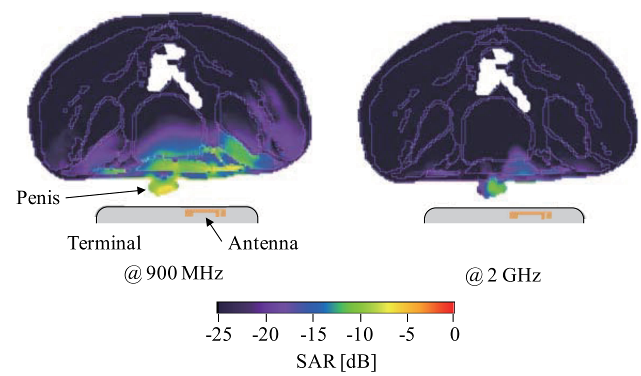

Fig. 15 Normalized SAR distributions at 900 MHz and 2 GHz for the male when the tablet computer model was placed at $z = -100$ mm.

thicker in the female model than in the male model. In addition, the SAR_{10g} value at $z = -100$ mm for the male model is approximately 1.5 dB lower than that at $z = 0$ for both frequencies. Figure 15 shows the SAR distributions at $z = -100$ mm normalized by the maximum SAR value at $z = 0$. It is shown that the distance between the skin and the antenna is larger than other height positions for the male model owing to the penis. Also, the SAR_{10g} values for the testicles at $z = -100$ mm for 900 MHz and 2 GHz are approximately 10.6 and 20.1 dB lower than those for all tissues of the male model, respectively. The relative standard deviations of SAR_{10g} for the different height at 900 MHz and 2 GHz for each human model are within 40%.

In Sect. 3.4, the variability of SAR_{10g} for the different tilts for the male model is larger than that for the female model, similar to the tendency shown in Sect. 3.2 because of the thickness of the fat layer and the shape of the abdomen, which are different for males and females. Focusing on $\alpha = 75°$, the SAR_{10g} values for both human models are higher than those for the original position. This is because the radiating plate of the 3G antenna faced the $+z$-direction when the tablet computer model was placed at the original position, whereas upon tilting the tablet computer model, the radiating plate faced the human body. Thus, the electric field was particularly concentrated in the narrow space between the tablet computer and the human body in the case of $\alpha =$

75°. The relative standard deviations of SAR_{10g} for the different tilts at 900 MHz and 2 GHz for each human model are within 20%.

The larger variability of SAR_{10g} for the seated model does not appear in comparison with that for various configurations of the tablet computer. This is because the peak values of SAR_{10g} appear at the abdomen in all cases, similar to those for the standing model. The SAR_{10g} values for the testicles at 900 MHz and 2 GHz in the seated model were 17.6 and 26.5 dB lower than those for all tissues of the male model, respectively.

In the further study, it is necessary to estimate SARs from a tablet computer for children, pregnant females, and their fetuses. This is because the shapes of the bodies of a child and a pregnant female are different from those of an adult male and female. Recently, the use of smart phones, which are multifunction mobile phones with various antennas such as the 3rd- and 4th-generation wireless communication systems and the Wi-Fi system, has also become widespread. In addition, a characteristic of the new types of the wireless radio terminals is simultaneously communicating and emitting radio waves, e.g., 3G and Wi-Fi. Therefore, it is also important to evaluate SARs for the human body due to different wireless communication systems and the simultaneous communication from smart phones and other tablet computers.

5. Conclusion

In this paper, we used numerical analysis to evaluate the variability of peak SAR_{10g} imposed by various configurations of a tablet computer on the human body. For these calculations, numerical models of a Japanese male and female were employed. We considered the 3G antenna (900 MHz and 2 GHz) in the tablet computer model as the radiator of EM waves.

We found that SAR_{10g} for different directions of the tablet computer was significantly affected by the relative position between the 3G antenna and the human body, i.e., −7.3 dB to −22.6 dB. When the tablet computer was moved along the z-axis in front of the abdomen, the maximum difference of the peak SAR_{10g} is 3.6 dB in the male model at 900 MHz. On the other hand, such remarkable difference did not appear for the other conditions, i.e., the male model at 2 GHz and the female models at both frequencies. We also confirmed that SAR_{10g} for the human body increased when the tablet computer is tilted so that the tablet computer faces the abdomen of the human. Peak SAR_{10g} for the human body due to exposure from the tablet computer does not strongly depend on the posture in this case, i.e., at most ±1.5 dB. Finally, the variability of SAR_{10g} from the 3G antenna in the tablet computer in close proximity to the abdomen as can be seen in the evaluations of Sects. 3.2 to 3.4 is affected by the thickness of the layer of the epidermal tissues and the shape of the abdomen.

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Akihiro Tateno was born in Chiba, Japan, in October 1988. He received the B.E. and M.E. degrees in electrical engineering from Chiba University, Chiba, Japan, in 2011 and 2013, respectively, and is currently working toward the Ph.D. degree at Chiba University. His main interests include the evaluation of the interaction between the EM field and human body.

Tomoaki Nagaoka received the Ph.D. degree in medical science from Kitasato University, Kanagawa, Japan, in 2004. He is currently a Senior Researcher with the Electromagnetic Compatibility (EMC) Laboratory, Applied Electromagnetic Research Institute, National Institute of Information and Communications Technology, Tokyo, Japan. His main research interests include biomedical EM compatibility and medical image analysis. Dr. Nagaoka is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), the IEEE Engineering in Medicine and Biology Society, and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of several awards, including the 2004 Best Paper Award of Physics in Medicine and Biology, the 2007 Young Researcher Award of the IEICE, the 2008 Young Scientist Award of International Scientific Radio Union, the 2011 Outstanding Paper Award of the IEEE Africon and the 2011 Best paper award of the ISABELL' 11.

Kazuyuki Saito was born in Nagano, Japan, in May 1973. He received the B.E., M.E., and D.E. degrees in electronic engineering from Chiba University, Chiba, Japan, in 1996, 1998 and 2001, respectively. He is currently an Associate Professor with the Center for Frontier Medical Engineering, Chiba University. His main interest is in the area of medical applications of microwaves including microwave hyperthermia. Dr. Saito is a member of the Institute of Electrical, Information and Communication Engineers (IEICE), Japan, the Institute of Image Information and Television Engineers of Japan (ITE), and the Japanese Society for Thermal Medicine. He was the recipient of the IEICE Antennas and Propagation Society (AP-S) Freshman Award, the Award for Young Scientist of the URSI General Assembly, the IEEE AP-S Japan Chapter Young Engineer Award, the Young Researchers' Award of the IEICE, and the International Symposium on Antennas and Propagation (ISAP) Paper Award in 1997, 1999, 2000, 2004, and 2005 respectively.

Soichi Watanabe received the B.E., M.E., and D.E. degrees in electrical engineering from Tokyo Metropolitan University, Tokyo, Japan, in 1991, 1993, and 1996, respectively. He is currently with the National Institute of Information and Communications Technology, Tokyo, Japan. His main research interest is biomedical EM compatibility. Dr. Watanabe is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan, the Institute of Electrical Engineers (IEE), Japan, and the Bioelectromagnetics Society. He was a member of the Standing Committee on Physics and Engineering of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) since 2005 and now is a member of the Main Commission of the ICNIRP since 2012. He was the recipient of the 1996 Young Scientist Award of the International Scientific Radio Union, the 1997 Best Paper Award of the IEICE, and the 2004 Best Paper Award (The Roberts Prize) of Physics in Medicine and Biology.

Masaharu Takahashi was born in Chiba, Japan, in December 1965. He received the B.E. degree in electrical engineering from Tohoku University, Miyagi, Japan, in 1989, and the M.E. and D.E. degrees in electrical engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1991 and 1994, respectively. From 1994 to 1996, he was a Research Associate, and from 1996 to 2000, an Assistant Professor with the Musashi Institute of Technology, Tokyo, Japan. From 2000 to 2004, he was an Associate Professor with the Tokyo University of Agriculture and Technology, Tokyo, Japan. He is currently an Associate Professor with the Center for Frontier Medical Engineering, Chiba University, Chiba, Japan. His main interests are electrically small antennas, planar array antennas, and EM compatibility. Dr. Takahashi is a Fellow of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1994 IEEE Antennas and Propagation Society (IEEE AP-S) Tokyo Chapter Young Engineer Award.

Koichi Ito received the B.S. and M.S. degrees from Chiba University, Chiba, Japan, in 1974 and 1976, respectively, and the D.E. degree from the Tokyo Institute of Technology, Tokyo, Japan, in 1985, all in electrical engineering. From 1976 to 1979, he was a Research Associate at the Tokyo Institute of Technology. From 1979 to 1989, he was a Research Associate at Chiba University. From 1989 to 1997, he was an Associate Professor at Chiba University, and is currently a Professor at the Department of Medical System Engineering, Chiba University. From 2005 to 2009, he was Deputy Vice-President for Research, Chiba University. From 2008 to 2009, he was Vice-Dean of the Graduate School of Engineering, Chiba University. Since April 2009, he has been appointed as Director of Center for Frontier Medical Engineering, Chiba University. In 1989, 1994, and 1998, he visited the University of Rennes I, France, as an Invited Professor. He has been appointed as Adjunct Professor to the University of Indonesia since 2010. His main research interests include analysis and design of printed antennas and small antennas for mobile communications, research on evaluation of the interaction between electromagnetic fields and the human body by use of numerical and experimental phantoms, microwave antennas for medical applications such as cancer treatment, and antennas for body-centric wireless communications. Dr. Ito is a Fellow of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, a member of the American Association for the Advancement of Science, the Bioelectromagnetics Society, the Institute of Image Information and Television Engineers of Japan (ITE) and the Japanese Society for Thermal Medicine. He served as Chair of the Technical Group on Radio and Optical Transmissions, ITE, from 1997 to 2001, Chair of the Technical Committee on Human Phantoms for Electromagnetics, IEICE, from 1998 to 2006, Chair of the Technical Committee on Antennas and Propagation, IEICE, from 2009 to 2011, Chair of the IEEE AP-S Japan Chapter from 2001 to 2002, Vice-Chair of the 2007 International Symposium on Antennas and Propagation (ISAP2007), General Chair of the 2008 IEEE International Workshop on Antenna Technology (iWAT2008), Co-Chair of ISAP2008, an AdCom member for the IEEE AP-S from 2007 to 2009, an Associate Editor for the IEEE Transactions on Antennas and Propagation from 2004 to 2010, a Distinguished Lecturer for the IEEE AP-S from 2007 to 2011 and General Chair of ISAP2012. He currently serves as Chair of the IEEE AP-S Committee on Man and Radiation (COMAR), and a Councilor to the Asian Society of Hyperthermic Oncology (ASHO). He has been elected as a delegate to the European Association on Antennas and Propagation (EurAAP) since 2012.