SAFETY LEVEL OF INCIDENT FIELDS TO A HUMAN HEAD FROM PORTABLE RADIO TRANSMITTERS: THEORETICAL ANALYSIS

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1. Introduction

A rapid increasing use of electromagnetic (EM) devices in recent years has being concerned about a potential biological hazards of EM radiation, and the radiation safety standards have been established in many countries. Most of these standards have the exclusion clause for near field exposure.

For example, concerning the low power radiation devices as a portable radio transmitter, ANSI C.95-1(1982) recommends as follows: "At frequency between 300 kHz and 1 GHz, the protection guides may be exceeded if the radio frequency (RF) input power of the radiating device is 7 W or less." However, this recommendation uncertainly assures that the clause is consistent with the basic limitation as the localized specific absorption rate (SAR) of 8 W/kg. Moreover, it has no relaxation clause for the radiation devices with input power of more than 7 W. Recently the recommendations including these relaxation clauses have proposed[1][2].

The purpose of this study is to be clear how far a head should be kept away from antenna for the exclusion clause consisting with the basic limitation, and to confirm property of the relaxation clause in the case of portable radio transmitters.

2. Theory

In the problem of EM exposure of a human head to the near fields of portable radio transmitters, the theoretical analysis is applicable. The theoretical formula is given by Amemiya and Uebayashi[3]. However, the expressions in the paper is so complex that we rearrange them as follows.

Fig.1 shows the position of linear antenna respect to a rectangular and spherical coordinate system having its origin at a center of sphere. Let P (R, θ, ϕ) in Fig.1 be an observation point, and $Q(R_o, \theta_o, \phi_o)$ be a source point, where $-\pi/2<\theta<\pi/2$, and $-\pi/2<\theta_o<\pi/2$.

For the infinitesimal electric dipole in the radial direction, electric field of inside or outside sphere is obtained from

$$\boldsymbol{E}_1=-E_o e^{-i\omega t}\sum_{n=1}^{\infty}(2n+1)h_n^{(1)}(k_2R_o)\ b_n^t \boldsymbol{n}_n^{(1)}(k_1R) \qquad (1)$$

$$\boldsymbol{E}_2=-E_o e^{-i\omega t}\sum_{n=1}^{\infty}(2n+1)h_n^{(1)}(k_2R_o)\,[\boldsymbol{n}_n^{(1)}(k_2R)+b_n^r \boldsymbol{n}_n^{(3)}(k_2R)] \qquad (2)$$

where $E_o=\omega\mu I\ell/4\pi R_o$, $I\ell$ is the current moment, b_n^t and b_n^r are the coefficients given by Stratton[4] and ref.[5], and $h_n^{(1)}(z)$ is the first kind spherical Hankel function. The spherical vector harmonics $\mathbf{n}_n$ is written by

$$\boldsymbol{n}_n(kR)=n(n+1)\frac{z_n(kR)}{kR}P_n(\cos\gamma)\boldsymbol{i}_R+\frac{[kRz_n(kR)]'}{kR}\frac{\partial}{\partial\theta}P_n(\cos\gamma)\boldsymbol{i}_\theta+\frac{[kRz_n(kR)]'}{kR}\frac{1}{\sin\theta}\frac{\partial}{\partial\varphi}P_n(\cos\gamma)\boldsymbol{i}_\varphi$$

where $\cos\gamma=\cos\theta\cos\theta_o+\sin\theta\sin\theta_o\cos(\phi-\phi_o)$, $P_n(x)$ is the first kind Legendre function, and $z_n(z)$ means either the first kind spherical Bessel function $j_n(z)$ or $h_n^{(1)}(z)$.

For the infinitesimal electric dipole in the direction of θ, electric field of inside or outside sphere is obtained from

$$\boldsymbol{E}_1=-E_o e^{-i\omega t}\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\{[k_2R_oh_n^{(1)}(k_2R_o)]\ a_n^t\boldsymbol{m}_{on}^{(1)}(k_1R)+[k_2R_oh_n^{(1)}(k_2R_o)]'\ b_n^t\boldsymbol{n}_{en}^{(1)}(k_1R)\} \tag{3}$$

$$\boldsymbol{E}_2=-E_o e^{-i\omega t}\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\{[k_2R_oh_n^{(1)}(k_2R_o)]\ [\boldsymbol{m}_{on}^{(1)}(k_2R)+a_n^r\boldsymbol{m}_{on}^{(3)}(k_2R)]+[k_2R_oh_n^{(1)}(k_2R_o)]'\ [\boldsymbol{n}_{en}^{(1)}(k_2R)+b_n^r\boldsymbol{n}_{en}^{(3)}(k_2R)]\} \tag{4}$$

where a_n^t and a_n^r are the coefficients given by refs.[4] and [5]. The spherical vector harmonics $\mathbf{m}_{on}$ and $\mathbf{n}_{en}$ are given by

$$\boldsymbol{m}_{on}(kR)=z_n(kR)\frac{1}{\sin\theta\sin\theta_o}\frac{\partial^2}{\partial\varphi\partial\varphi_o}P_n(\cos\gamma)\boldsymbol{i}_\theta-z_n(kR)\frac{1}{\sin\theta_o}\frac{\partial^2}{\partial\theta\partial\varphi_o}P_n(\cos\gamma)\boldsymbol{i}_\varphi$$

$$\boldsymbol{n}_{en}(kR)=n(n+1)\frac{z_n(kR)}{kR}\frac{\partial}{\partial\theta_o}P_n(\cos\gamma)\boldsymbol{i}_R+\frac{[kRz_n(kR)]'}{kR}\frac{\partial^2}{\partial\theta\partial\theta_o}P_n(\cos\gamma)\boldsymbol{i}_\theta+\frac{[kRz_n(kR)]'}{kR}\frac{1}{\sin\theta}\frac{\partial^2}{\partial\varphi\partial\theta_o}P_n(\cos\gamma)\boldsymbol{i}_\varphi\ .$$

Referring to eqs.(1) and (3), electric field inside sphere for the linear antenna located at $y=0$, $z=z_o$, is derived as follows:

$$\boldsymbol{E}_1=-E_o e^{-i\omega t}\frac{1}{l^*}\int_{-\infty}^{\infty}dx'\,f(x')\cos\theta_o\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\,[\,n(n+1)h_n^{(1)}(k_2R_o)b_n^t\boldsymbol{m}_n^{(1)}(k_1R)\sin\theta_o+\{[k_2R_oh_n^{(1)}(k_2R_o)]\ a_n^t\boldsymbol{m}_{on}^{(1)}(k_1R)+[k_2R_oh_n^{(1)}(k_2R_o)]'\ b_n^t\boldsymbol{n}_{en}^{(1)}(k_1R)\}\cos\theta_o]$$

where current distribution $I=I_of(x)$, $E_o=\omega\mu I_o\ell^*/4\pi z_o$, and $\ell^*=\int f(x')dx'$. We assume that the current distribution of $\lambda/2$ dipole antenna is

$$I=I_o\cos k_2x,\ \text{where}\ -h<x<h\ \text{and}\ h=\lambda/4\ .$$

3. Results

3.1 Calculation of Peak SAR

By use of $\mathbf{E}_1$, SAR is defined as

$$SAR=\sigma|\boldsymbol{E}_1|^2/\rho\,[W/kg]$$

where ρ and σ is the density and conductivity, respectively, of biological tissues. In following calculation we use the dielectric constants of 2/3 muscle models[6]. The radius of sphere is a = 10 cm. For simplifying our discussion, we do not mention the perturbation of antenna impedance with approaching to the sphere.

Fig.2 shows the distance dependence of the peak SAR for a half-wavelength dipole driven by 1 W. From this figure we can see that the peak SAR is inversely as the square of distance. Fig.3 illustrates the frequency dependences of the peak SAR per watt, where s denotes the distance between the surface of sphere and antenna.

Fig.4 shows the frequency dependence of the peak SAR normalized by incident electric field strength at the front of sphere. The normalizing field strength is 61.4 V/m, corresponding to plane-wave equivalent power density of 1 mW/cm^2. In this figure dashed line denotes the SAR's peak values in the plate model exposed to plane wave. These curves are almost convergent in the frequency range of more than 3 GHz.

3.2 Limitation of Power of Transmitter

From Fig.3 we can calculate the upper limit of transmitter's power satisfying the limitation of localized SAR of 8 W/kg. The results are shown in Fig.5. The thick lines denote the limit for the peak SAR averaged over 1 cm^3 of tissue in plane-wave exposure, and dashed line denotes the exclusion for low power devices of Japanese guidelines[2]. From this figure we can see that the distance for consisting the basic SAR limitation is about 7 cm.

3.3 Limitation of Incident Power Density

In a similar way to 3.2, we can obtain the upper limit of incident electric field strength from Fig.4. The results converted to plane-wave equivalent power density are shown in Fig.6. The thick lines denote the limit with regard to the averaged peak SAR in plane-wave exposure, and dashed line denotes the power density equivalent to the electric field strength limit of Japanese guidelines[2]. From this figure we can see that the relaxation of limitation according to only electric field measurement is dangerous when the distance is very short. In this case, it seems that the contribution of magnetic field become relatively very large.

4. Conclusion

The exclusion clause with regard to the low power radiation devices is consistent with the localized SAR limitation of 8 W/kg if only a human head is kept away from the antenna more than 7 cm. In applying the relaxation clause, it involves some risk to evaluate from measurement of only electric field strength.

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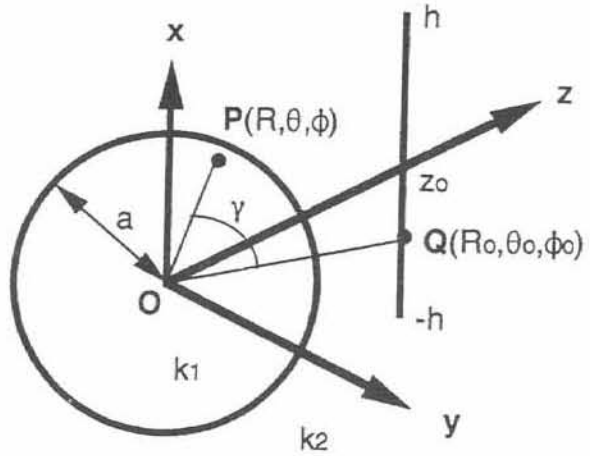

Fig.1 The spherical human head model exposed by a dipole antenna.

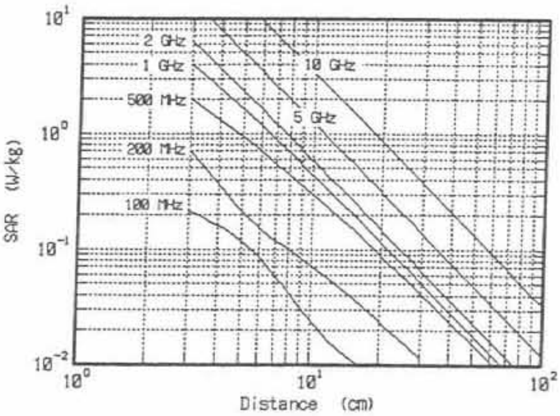

Fig.2 Distance dependence of peak SAR of sphere exposed to the near field of a $\lambda/2$ dipole. (Power = 1 W, a = 10 cm)

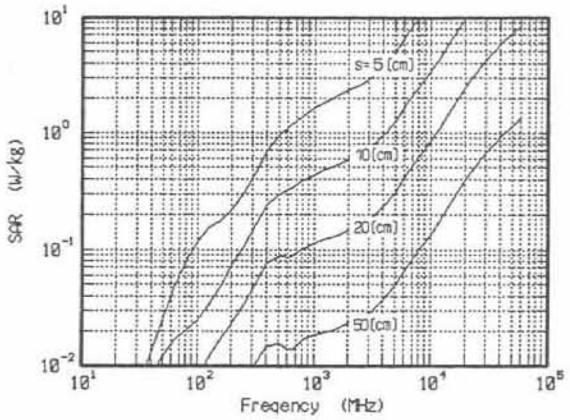

Fig.3 Frequency dependence of peak SAR of sphere exposed to the near field of a $\lambda/2$ dipole. (Power = 1 W, a = 10 cm)

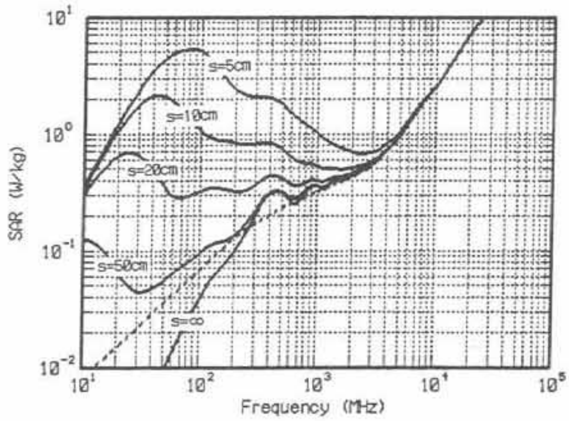

Fig.4 Frequency dependence of peak SAR of sphere exposed to the near field of a $\lambda/2$ dipole. (E_i = 61.4 V/m, a = 10 cm)

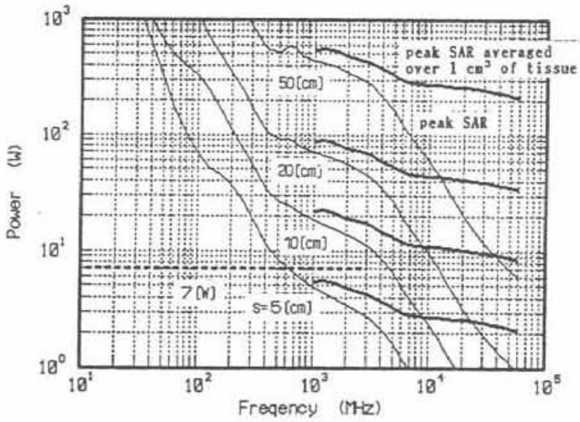

Fig.5 Transmitter's power satisfied with the limitation of peak SAR of 8 W/kg. (a = 10 cm)

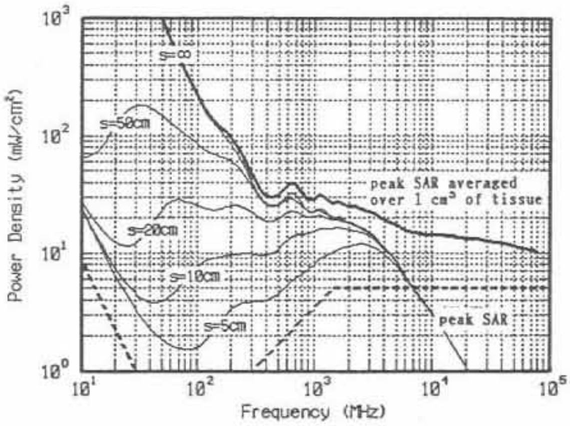

Fig.6 Plane-wave equivalent power density satisfied with the limitation of peak SAR of 8 W/kg. (a = 10 cm)