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Characteristics of Specific Absorption Rate (SAR) in Electromagnetic (EM) Dosimetry

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Abstract - The SI unit of specific absorption rate (SAR) in W/kg in the electromagnetic (EM) field as non-ionizing radiation is exactly same as the SI unit of absorbed dose rate in Gy/s in the ionizing radiation field. The SI unit of both physical quantities can be expressed in $[m^2 \cdot s^{-3}]$. Where, the unit of absorbed dose, Gy stands for Gray. In EM biological interactions, the SAR equations are derived and the characteristics of EM field energy absorption in terms of the SAR are discussed and described on the mathematical basis.

Key Words: electromagnetic (EM) dosimetry, mass density, conductivity, permittivity, energy absorption, specific absorption rate (SAR), electromagnetic (EM) field, skin depth.

Introduction

The specific absorption rate (SAR) is a measure of the rate of energy that is absorbed or dissipated in any part of the human body due to the use of equipment such as mobile phones or by human exposure close to other transmitting sources. Where, "specific" refers to the normalization to mass of the object. Guidelines for the acceptable SAR exposure levels are set in the U.S. by the Federal Copmmunications Commission (FCC), in the U.K. by the National Radiological Protection Board (NRPB) and a new standard for Europe has been prepared by the Comite Europeen de Normalisation Electrotechnique(CENELEC). SAR can be predicted computationally but experimental assessment offers advantages of flexibility and avoids the need to build sophisticated mathematical models of complex electromagnetic (EM) field sources and absorbing geometries. In electromagnetic (EM) field dosimetry, usually SAR is expressed in watts per kilogram (W/kg) or milliwatts per gram (mW/g).

Electromagnetic (EM) Dosimetry

The electromagnetic (EM) dosimetry can be divided into two categories. one is macroscopic dosimetry, and the other is microscopic dosimetry. Historically, much more works has been done in macroscopic dosimetry than in microscopic dosimetry. In macroscopic dosimetry, the EM fields are determined as an average over small volume of space such as in mathematical cells that are cm or mm in size. For example, if the mathematical cell size is 1 mm on a side, then the **E** field in a given mathematical cell is assumed to have the same value everywhere within the 1 mm^3 volume of that cell. In other words, the **E** field is averaged over the volume of the cell. The **B** field is also averaged over the cell. These are called macroscopic EM fields. In microscopic dosimetry, however, the EM fields are determined at a microscopic level such as the cellular level in biological systems. Or, equivalently, the mathematical cells over which the EM fields are determined are microscopic in size. However, the EM dosimerty consists

of two main parts. First, the incident **E** and **B** fields must be determined. Typically, these fields are determined either from the nature of the sources producing them or by measurements. And second, the internal **E** and **B** fields inside the object must be determined, either by calculation or by measurements. Where, the relationship between the incident EM fields and the internal EM fields is a strong function of the frequency of the incident EM fields, the size and shape of the object, and the electromagnetic properties of the object.

Electromagnetic (EM) Field Energy Absorption

In many EM field interactions, the **E** field can transfer energy to electric charges through the forces it exerts on them, but the **B** field does not transmit energy to charges. The forces that **B** exerts on the charges can change their directions, but not their energy because these **B** field forces are always in a direction perpenicular to the velocities of the charges. However, the **B** field can transfer energy through forces on permanent magnetic dipoles. Accordingly, the **B** field effect is not prominent in EM biological interactions because the biological tissue is mostly nonmagnetic and contains very few permanent magnetic dipoles.

The average SAR can be determined by measurement of the total absorbed power, the time rate of energy transferred to charges, in an exposed object such as biological tissue. For the special case of sinusoidal steady-state EM fields, the absorbed power, P_A in an infinitesimal volume element ΔV of a material is given by

$$P_A = (\sigma + \omega \cdot \varepsilon_0 \cdot \varepsilon'') E^2_{rms} \cdot \Delta V \text{ watts (W)} \quad (1)$$

where, σ is conductivity in siemens per meter (S/m), ω is the radian frequency in radians per second (r/s), ε_0 is permittivity of free space in farads per meter (F/m) and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, and E_{rms} is the root-mean-square (rms) value of the magnitude of **E** at that point which is given by $E_{rms} = E/2^{1/2}$. Since ΔV has units of m^3, the quantity $(\sigma + \omega \cdot \varepsilon_0 \cdot \varepsilon'') E^2_{rms}$ has units of W/m^3, which is the density of absorbed power. Accordingly, the average SAR is given by

$$SAR = (\sigma + \omega \cdot \varepsilon_0 \cdot \varepsilon'') E^2_{rms}/\rho \text{ watts/kilogram (W/kg)} \quad (2)$$

where, ρ is the mass density in kg/m^3. Since Eq. (2) is a point relation and thus often called the local SAR, the space average SAR for an object is obtained by calculating the local SAR at each point in the object. In Eq. (2), the SAR varies directly as both σ and ε'' which indicate how much energy will be absorbed by the material for a given **E**. Where, σ and ε'' are said to be indicators of the lossiness of materials. The greater the σ and the ε'', the greater the loss in the material. That is, the more power is absorbed for a given **E**. The ε'' can be calculated by the loss tangent, or dissipation factor, which is defined as $\tan\delta = \varepsilon''/\varepsilon'$. Tables of the properties of dielectrics often give ε' and $\tan\delta$. Where, dielectrics are nonmetallic materials with negligible σ. However, calculations have shown that the average ε' and ε'' for the whole human body are equal to approximately two-thirds that of muscle tissue. The permittivity of biological tissue is a strong function of frequency in the EM fields and generally decreases with frequency. This manifests the inability of the charges in the tissue to respond to the higher frequencies of the applied fields, thus resulting in lower permittivity values. In tissue, the ε'' represents mostly ionic conductivity and absorption due to relax-

ational processes, including friction associated with the alignment of electric dipoles and with vibrational and rotational motion in molecules. The permeability of biological tissue is essentially equal to that of free space. In other words, biological tissue is nonmagnetic. Meanwhile, another common definition is that of effective conductivity, σ_{eff}, which is defined as $\sigma_{eff} = (\sigma + \omega \cdot \varepsilon_0 \cdot \varepsilon'')$. Thus in terms of effective conductivity, the SAR is given by

$$SAR = \sigma_{eff} \cdot E^2_{rms} / \rho \quad (W/kg) \qquad (3)$$

Materials are often characterized by ε' and σ_{eff}, where σ_{eff} is frequently referred to as just "conductivity." Therefore, in terms of the peak value of **E**, the SAR is given by

$$SAR = \sigma_{eff} \cdot E^2/2\rho \quad (W/kg) \qquad (4)$$

In addition, two other definitions are used in the EM field theory. One is magnetic field strength or magnetic field intensity, defined as $\mathbf{H} = \mathbf{B}/\mu$ which has units of ampere per meter (A/m). **H** is often more convenient to use than **B** in describing EM wave interactions and where, the permeability μ has units henrys per meter (H/m). In practice, both **B** and **H** are often referred to simply as magnetic fields. The other is electric flux density or electric displacement, defined as $\mathbf{D} = \varepsilon \mathbf{E}$ which has units of coulombs per square meter (C/m^2). Sometimes using **D** is more convenient than **E** in EM field theory.

Characteristics of SAR

The penetration of incident EM fields into biological bodies decreases as frequency increases. This effect is illustrated in Fig. 1 which shows the skin depth as a function of frequency for a planewave incident on a dielectric halfspace having a permittivity and conductivity equal to two-thirds that of muscle tissue. The skin depth, δ, is defined as the depth at which the EM fields have decreased to e^{-1} (0.368) of their value at the surface of the body, where e=2.718 is the base of the natural logarithm. For a planewave impinging on a conducting halfspace, the skin depth is given by $\delta = [2/\omega \mu \sigma]^{1/2}$ in meters. The dielectric halfspace means half of all space is filled with one dielectric, and the other half is filled with another dielectric (often free space), with a planar interface between two. The energy absorbed by an object exposed to incident EM fields is a function of frequency and of the size, shape, and electric properties of the object. Therefore, the characteristics of energy absorption in terms of the SAR are described in this section, first at low frequencies where the wavelength is long compared with the size of the object and then at higher frequencies where resonance effects can occur.

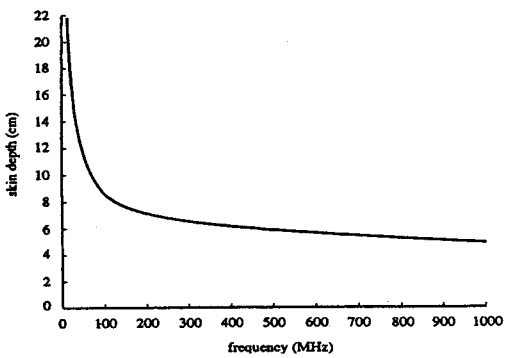

Fig. 1. Skin depth as a function of frequency.[1]

SARs at Low Frequencies

At frequencies low enough that the EM wavelength is large compared with the size of the object, the **E** and **B** fields are approximately uncoupled. In this frequency range, EM dosimetry consists of determining the internal fields due to the incident

E field acting alone and then due to the incident B field acting alone. In measuring or calculating the internal fields at low frequencies, various models would be used to represent humans or other animals. In early work, spherical models were used to represent human shape, but spheroidal and ellipsoidal models were used to represent animal shapes. Much useful information was obtained from spherical models. Those models were particularly useful for them because analytical solutions of closed form could be obtained very well at low frequencies. The characteristics of internal fields could be understood by such solutions. Later, other models with more realistic shapes were used both in measurements and in calculations. For measurements figurines were used, but for calculations, so-called block models were used. These block models consist of cubical mathematical cells arranged to approximate the shape of human and other animal bodies. In those cases, however, analytical solutions can not be obtained. Instead, therefore, numerical methods are used to calculate the internal fields. All those models described above provide solutions of Maxwell's equations and then mathematical expressions for the internal **E** and **H** fields. Some commonly used numerical methods are the moment method, the finite-element method, finite-difference time-domain (FDTD) method and finite-difference frequency-domain (FDFD) method, and impedance method. In recent years, the powerful computers have made it possible to execute more sophisticated EM dosimetry calculations at very low frequencies, too.

SAR as a Function of Frequency

In principle, the internal fields in any object irradiated by electromagnetic fields can be calculated by solving Maxwell's equations. In practice, this is very difficult and can be done only for a few special cases. From Poynting's theorem[2] which is a powerful statement of energy conservation, the general characteristics of the average whole-body SAR as a function of frquency for a model of an average man irradiated by an incident planewave with a

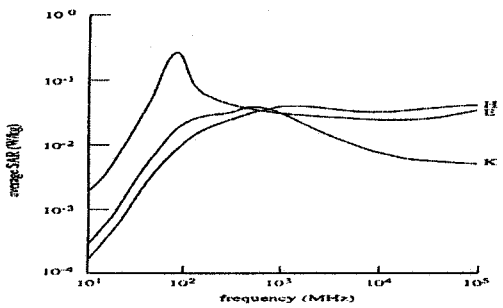

Fig. 2. Average whole-body SAR as a function of frequency.[3]

power density of 1 mW/cm^2 are shown in Fig. 2. For convenience, the Poynting vector, **P** = **E** x **H**, represents the instantaneous power transmitted through a surface per unit surface area. It is usually designated as **S**, is also known as energy-flux (power) density, and has units of watts per square meter (W/m^2). In Fig. 2, the calculated results are shown for models of an average man in free space for three polarizations, E, H, and K. There were several methods of calculations over various parts of the frequency range. At low frequencies, a long-wavelength approximation was a method of SAR calculation. Up to approximately the resonant frequency, however, the extended-boundary condition method (EBCM) was used. Above that, the iterative EBCM was introduced as the IEBCM. But other methods include the classical solution of Maxwell's equations for cylinders and the surface integral equation (SIE) method. Moment-method frequency-domain (MMFD) calculations in

block models have provided much useful dosimetry information. FDFD methods and finite-element methods have also been used in EM dosimetry calculations. For all three polarizations, the SAR varies approximately as the square of the frequency at low frequencies.

Effects of Polarization on SAR

The effects of polarization can be explained in terms of two general behaviors. These general behaviors are (1) the internal **E** field is generally greater when the $\mathbf{E}_{inc}$ is mostly "parallel" to the body surface than when it is mostly "normal" to the body surface, (2) the internal **E** is generally greater when thhe as $\mathbf{E}_{Hint}$, respectively. Then, the polarization effects are summarized as shown in Table 1.

Conclusions

SAR is an important quantity in EM dosimetry both because it gives a measure of the energy absorption that can be manifest as heat and because it gives a measure of the internal fields which could affect the biological system in ways other than through ordinary heat. The internal fields, and hence the SAR, are a strong function of the incident fields, the frequency, and the properties of the object irradiated. Since any biological effects would be caused by internal fields, not incident fields, determination of SARs in

Table 1. Summary of Explanations for the Effects of Polaization on SAR[1]

Polarization	$\mathbf{E}_{inc}$	$\mathbf{H}_{inc}$	$\mathbf{E}_{Eint}$	$\mathbf{E}_{Hint}$	Relative SAR
E	Mostly parallel	Intercepts large C.S.	Strong	Strong	Highest
K	Mostly normal	Intercepts large C.S.	Weak	Strong	Middle
H	Mostly normal	Intercepts small C.S.	Weak	Weak	Lowest

Note: C.S. stands for cross section.

cross-sectional area is smaller. These explanations are based on the low-frequency concepts that the **E** and **H** are approximately uncoupled at low frequencies and that the internal **E** is the sum of the internal **E** produced by the $\mathbf{E}_{inc}$ and by the $\mathbf{H}_{inc}$. At higher frequencies, however, the effects are more complicated because **E** and **H** are coupled together and can strongly interact, but the ideas may have some validity even at higher frequencies. For convenience in discussions of how polarization affects SARs, let denote the internal **E** field produced by $\mathbf{E}_{inc}$ as $\mathbf{E}_{Eint}$ and the internal **E** field produced by $\mathbf{H}_{inc}$ humans and experimental animals for given conditions is important. However, EM dosimetry must carefully be taken into account in animal experiments in which the results are to be extrapolated to those expected in humans under similar conditions. In particular, "Handbook of Biological Effects of Electromagnetic Fields" is recommended as a reference for a further study on EM dosimetry.[4] At the mobile telecommunication era, therefore, the Health Physics Community in Korea should have their interests in the EM dosimetry research activities of International Commission on Non-Ionizing Radiation

Protection(ICNIRP) in Germany.[5]

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