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Radio Frequency Electromagnetic Exposure:
Tutorial Review on Experimental Dosimetry

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Radio frequency (RF) dosimetry is the quantification of the magnitude and distribution of absorbed electromagnetic energy within biological objects that are exposed to RF fields. At RF, the dosimetric quantity, which is called the specific absorption rate (SAR), is defined as the rate at which energy is absorbed per unit mass. The SAR is determined not only by the incident electromagnetic waves but also by the electrical and geometric characteristics of the irradiated subject and nearby objects. It is related to the internal electric field strength (E) as well as to the electric conductivity and the density of tissues; therefore, it is a suitable dosimetric parameter, even when a mechanism is determined to be "athermal." SAR distributions are usually determined from measurements in human models, in animal tissues, or from calculations. This tutorial describes experimental techniques that are used commonly to determine SAR distributions along with the SAR limitations and unresolved problems. The methods discussed to obtain point, planar, or whole-body averaged SARs include the use of small E-field probes or measurement of initial rate of temperature rise in an irradiated object.

Key words: SAR, microwave, nonionizing radiation, electric field, conductivity, biological effects

INTRODUCTION

To study the biological effects of exposure to radio frequency (RF) electromagnetic (EM) radiation, experiments that cannot be performed ethically on human beings are performed on animals, tissue preparations, and cell cultures. RF energy interactions with biological materials (in a physical sense) are complex. These interactions may produce highly nonuniform distributions of EM fields within the object, regardless of the external exposure field uniformity. The fundamental quantities associated with the interaction are the electric and magnetic field strengths induced within these tissues and the currents and energy associated with these internal fields. The internal fields and currents are related to the incident external electric and magnetic fields in a very complicated manner. The results obtained from animal and in vitro experiments are not always directly applicable to human beings. Not only are differences in biological endpoints important in RF research, one must also consider the difficult problem of extrapolating the dosimetric results from laboratory animals or cell cultures to human beings [Michaelson and Lin, 1987].

Unlike ionizing radiation (radiation at or above the ultraviolet region of the EM spectrum), lower frequency nonionizing RF radiation with the same external EM field intensity can produce significantly different levels of energy absorption. This frequency dependence, in turn,

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can cause markedly different biological effects in various animal species or tissue cultures [Johnson and Guy, 1972; Chou and Guy, 1977; Chou and Guy, 1985; Stuchly and Stuchly, 1986; Guy, 1987]. For example, after observing a behavioral effect in rats exposed to a 2450 MHz microwave field at an incident power density of 0.5 mW/cm^2, one cannot conclude that the external microwave irradiation at that frequency and power density will elicit an analogous behavioral response in human beings. By the same token, the absence of any effect on flying insects exposed to microwave radiation at 100 mW/cm^2 does not assure safety for humans exposed to that intensity. To interpret a biological effect, one must determine the internal field strength or the energy dose that can cause such an effect in the experimental subject.

In this paper, the importance of RF dosimetry, the factors affecting RF energy absorption in tissue, and the experimental methods of determining specific absorption rate (SAR) will be discussed. The quantification of SAR to be discussed includes localized, planar (two-dimensional), and whole-body measurements. RF dosimetry, per se, refers only to energy absorption in tissues and not to exposure fields external to the biological system. Instrumentation and methods for measuring external field strengths or power densities can be found in numerous publications [Stuchly and Stuchly, 1986; Michaelson and Lin, 1987; Bassen and Babij, 1990; ANSI/IEEE, 1992b]. Examples of applying these techniques to common RF sources are described in a report from the National Council on Radiation Protection and Measurements [NCRP, 1994]. The discussions herein focus primarily on the experimental aspects of SAR measurements and not on theoretical calculations for determining the SAR, such as the finite-difference time-domain (FDTD) method [Taflove, 1995]. Durney et al. [1986] and Gandhi [1990] have provided extensive information on the use of theoretical techniques. Details of SAR measurement practices can be found in the American National Standards Institute (ANSI)/Institute of Electrical and Electronics Engineers (IEEE) C95.3-1992 standard [ANSI/IEEE, 1992b]. Examples of SAR measurements relating to cellular and mobile telephones will be used to illustrate the complexity of RF dosimetry. Finally, limitations and unresolved problems associated with the use of SAR will be addressed.

BASIC RF PARAMETERS

A few fundamental parameters of external exposure to EM fields are in order. These parameters are important in establishing the SAR in a biological object that is exposed to an RF field. Some of these parameters are illustrated in Figure 1. More definitions can be found in the ANSI/IEEE documents [ANSI/IEEE, 1992a,b].

Electric field strength is a vector quantity (usually designated as E) that describes the force on an infinitesimally small electric charge at a given point in an electric field (produced by charges). The unit of electric field strength is volts per meter (V/m). *Magnetic field strength* is a vector quantity (usually designated as H) that describes the force imposed on an infinitesimally small, moving, electrically charged particle at a given point in a magnetic field (produced by current). The direction of the force is perpendicular to the direction of the field and the motion of the particle. The unit of magnetic field strength is amperes per meter (A/m).

The *EM field* is the combination of a time-varying electric field and a magnetic field at a point in space. For every time-varying electric field, there is an accompanying time-varying magnetic field, and vice versa. *Exposure* is the irradiation or immersion of a biological object in EM fields that are external to and incident upon the object. The magnitude of an exposure depends on the strength and duration of the external EM fields. *Internal fields* are the EM fields that are induced inside the tissues of a biological object by external fields.

Whole-body exposure is the exposure of a biological object when the incident electric field and/or the magnetic field strengths are relatively uniform over the entire biological object. *Partial-body exposure* is the exposure of a biological object where the incident electric field and/or the magnetic field strengths are nonuniform over the biological object. The field strengths are small over some significant portion of the external surface of the exposed object.

The *dose* or *specific absorption* (SA) is the total amount of energy that is absorbed by a given mass within a biological object exposed to external EM fields. The SA is expressed in units of joules per kg (J/kg) or W-s per kg. The *dose rate* or *SAR* is the time rate at which energy is absorbed by a biological object exposed to EM fields. The SAR is expressed in W/kg or in mW/g. For more details, see Definition of SAR, below.

The *whole-body averaged SAR* is a single SAR value that represents the magnitude of the spatially averaged SAR throughout an exposed biological object. The *local SAR* is the SAR that represents the magnitude of the SAR in a small portion of an exposed biological object.

Frequency is the number of periods of sinusoidal variation per unit time. Frequency is measured in hertz (cycles per second). In RF radiation, the unit megahertz (MHz; one million hertz) is commonly used. *Wavelength* is the distance between corresponding maxima in the electric (or magnetic) field in a medium through which an RF EM wave is propagated. Wavelength and frequency are related by the following equation:

$$\lambda = v/f,$$

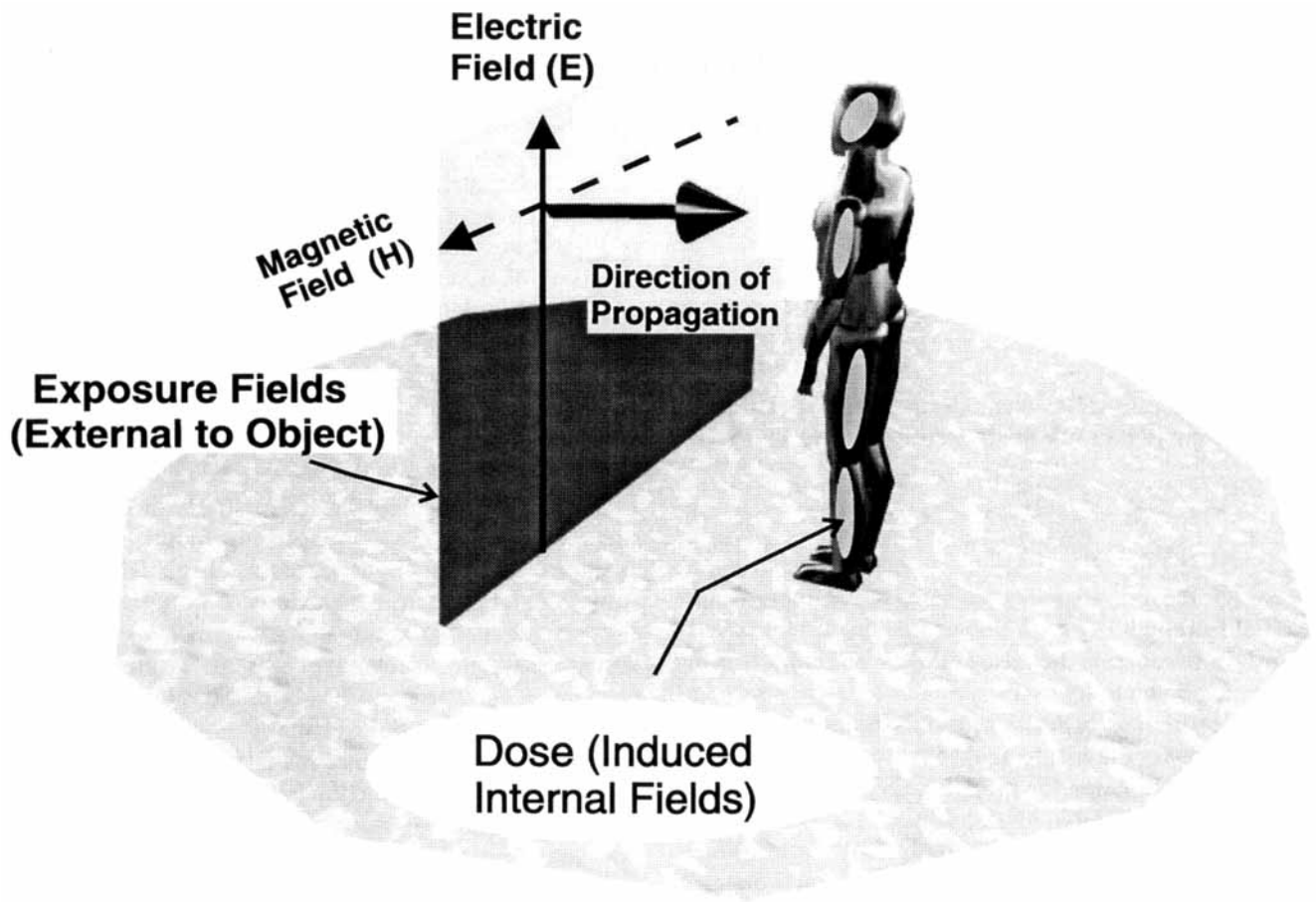

Fig. 1. Spatially uniform incident radio frequency (RF) fields and resulting nonuniform distribution of internal fields.

where λ = wavelength (meters), f = frequency (Hz), v = velocity of EM wave in media $= c/(\varepsilon_r)^{\frac{1}{2}}$, c = velocity of light in vacuum (~3×10^8 m/second), and ε_r = relative dielectric constant of the media. For a 300 MHz RF wave propagating through air, the wavelength is about 1.0 meter.

DEFINITION OF SAR

Coupling (transferring) EM energy to tissues is a complex function of many variables. The external incident field intensity may be expressed in a variety of units. Exposure data may be expressed in terms of power density (mW/cm^2), external electric field strength (V/m), or magnetic field strength (A/m). None of these data provides investigators with sufficient insight into how fields interact with biological tissue. A basic physical law (that of Grotthuss-Draper) states that a physical agent will have an effect only if it is inside a body. Consequently, the question arises as to the most suitable parameter(s) for quantifying the interaction of EM fields and biological systems. Schwan [1971] proposed the use of induced current density in tissue. An alternative is to use the internal electric field strength (E). Yet another option is to use the mass-normalized rate of energy absorption, or dose rate, a concept that was introduced to microwave research in the late 1960s [Justesen and King, 1970; Justesen, 1975]. Many investigators now rely on dose rate, which was formerly termed "absorbed power density" [Johnson and Guy, 1972]. This parameter was officially designated SAR by the National Council on Radiation Protection and Measurements [NCRP, 1981]. *The SAR is formally defined as the time derivative of the incremental energy absorbed by (dissipated in) an incremental mass contained in a volume of a given density.* The SAR definition also applies to magnetic SA (i.e., energy absorption by biomagnetite in magnetic fields). In absence the of magnetic materials, only electric fields need to be considered.

Technically, it makes no difference which of the above parameters (E, induced current, or SAR) is chosen for quantification, because they are all related by the following equations:

$$SAR = \frac{\sigma}{\rho} E^2 \quad (W/kg), \tag{1}$$

$$E = \left(\frac{\rho}{\sigma} SAR \right)^{\frac{1}{2}} \quad (V/m), \tag{2}$$

$$J = (\sigma \rho \, SAR)^{\frac{1}{2}} \quad (A/m^2). \tag{3}$$

The heating rate (HR) used in clinical hyperthermia applications [Chou, 1990] is also related to the SAR:

$$HR = \frac{SAR}{69.77 c_H} \quad (^\circ C/\min), \tag{4}$$

where E is the root-mean-square value of the induced electric field strength (V/m) in tissue, J is the current density (A/m^2) in tissue, ρ is the tissue density in kg/m^3, σ is the dielectric conductivity of the tissue in Siemens/m, and c_H is the specific heat capacity of the tissue in kcal/kg· °C.

ANSI was the first to adopt SAR as the fundamental dosimetry parameter for the RF exposure safety standard [ANSI, 1982]. No matter which of the parameters is used, the essential result is the quantification of the EM field in irradiated tissue. Among these parameters, SAR has been accepted widely as the quantification unit by researchers studying biological effects and medical applications of EM fields. Without quantitative measurement of the energy or field within an exposed object, it is difficult to compare research results from various animal species and different EM exposure parameters. Also, it is impossible to extrapolate biological effect research results to human beings in order to develop RF exposure safety guidelines.

In dosimetry studies, the SAR is treated as a linear quantity. The SARs obtained at high intensities and short exposures can be extrapolated to low-power exposure. Because the thresholds for biological effects may be frequency and modulation dependent, these parameters must also be specified in addition to the SAR data.

FACTORS THAT DETERMINE ENERGY ABSORPTION IN TISSUES

Dielectric Properties

The magnitude and spatial distribution of EM fields within biological tissues depend on the dielectric properties of tissue (dielectric constant and conductivity), which are dominated by the water content. Therefore, tissues can be divided into those with high water content, such as eye, muscle, skin, liver, and kidney, and those with low water content, such as fat and bone. Recently, Gabriel [1995] reported that bone material has a higher dielectric constant and conductivity than previously published. These results are being examined further. Other tissues that contain intermediate quantities of water, such as brain, lung, and bone marrow, have dielectric properties that lie between tissues with high and low water content. The dielectric constant and conductivity of tissues vary over a wide range and are frequency dependent. Data on tissue dielectric properties can be found in Johnson and Guy [1972], Durney et al. [1986], Foster and Schwan [1986], Michaelson and Lin [1987], Stuchly and Stuchly [1990], and Gabriel [1995].

Tissue Geometry and Size

The highest local SAR is usually at or near the surface of an externally exposed object. For curved surfaces and "resonant objects," high SARs ("hot spots") exist at various locations. A complex biological system, such as a human body, consists of multiple layers of tissue. Each layer has different dielectric properties and forms an EM boundary. When exposed to an RF field, the field propagates within the multilayered object. A portion of the energy is reflected from each boundary, and a portion is transmitted into the next layer. The amount of transmission and reflection at each boundary depends on the difference in dielectric properties of the tissues (characteristic impedance mismatch). Fat thickness, tissue curvature, and dimensions of the body, limbs, and head relative to the wavelength all affect the energy distribution. Johnson and Guy [1972], Durney et al. [1986], and Lin [1986] showed different absorption characteristics in spheroidal and cylindrical biological objects of various sizes exposed to incident plane waves.

Tissue Orientation and Field Polarization

It has been shown both theoretically [Durney et al., 1978] and experimentally [Gandhi et al., 1977] that the SAR in an exposed subject is maximal when the long axis of the body is parallel to the direction of a uniform external electric field. For example, consider a rat-sized ellipsoidal model exposed to a 10 MHz RF field with the electric field parallel to the long axis of the model. The average SAR is about 20 times higher than that occurring when the electric field is perpendicular to the long axis of the model. This example illustrates that, at this frequency, energy coupling in a freely moving rat exposed to a constant power density RF field may vary by about 20-fold, depending on the field or body orientation. The ratios are different at other frequencies. For in vitro experiments, Meltz et al. [1988] showed the orientation effect of a tissue culture flask on the SAR.

Field Frequency

In addition to the frequency dependence of dielectric properties, the strength and spatial distribution of internal fields also vary with frequency. For example, the local SAR was computed for a spherical head model with a constant intensity exposure at frequencies from 100 to 10,000 MHz. The computed maximum local SAR varied by more than 100 times [Johnson and Guy, 1972]. Calculation of the variation of average SAR with frequency for a human-sized sphere showed that, at low frequencies, the average SAR varies as the square of the frequency. At intermediate frequencies, the average SAR increases directly in proportion to frequency and reaches a maximum at the resonance frequency [Lin et al., 1973]. In another theoretical study, SAR calculations for exposed ellipsoids showed that absorption increases proportionally with the square of the frequency. The local SAR reaches a maximum at a specific frequency, i.e., whole-body resonance. At resonance, the length of the long axis of the exposed body is approximately four-tenths of the field wavelength in air [Durney et al., 1978].

Source Configuration

Far field is a term that describes a plane-wave exposure field. A plane wave is characterized by electric and magnetic fields that are spatially uniform and mutually perpendicular (Fig. 1). The far field typically begins at a distance of $2D^2/\lambda$ from the radiating source, where D is the longest dimension of the radiating structure, and λ is the wavelength in air. In the far field, with the exception of polarization, the SAR is independent of source configuration (there is no interaction or "coupling" between the source and the object). However, in the *near field* (closer than $2D^2/\lambda$), energy coupling depends on the source shape and size, e.g., an operator's position relative to an RF dielectric heater or heat sealer [Stuchly and Lecuyer, 1985]. Kuster and Balzano [1992] have shown that, in the immediate vicinity of resonant RF current sources (such as a hand-held cellular telephone), the SAR in an exposed homogenous model is associated primarily with the current induced by the RF magnetic field. In another example, the SAR distributions of waveguide hyperthermia applicators also show strong source configuration dependence [Chou, 1992]. A water bolus is usually placed in the near field of the applicator to cool the skin and subcutaneous fat. The presence of this bolus in the near field dramatically affects the SAR distribution and coupling.

Exposure Environment

The quantity of energy absorbed by a body in an RF field depends on environmental factors. Factors include whether the subject is exposed in free space, on a ground plane, near metal reflectors, or in an electrically conductive structure, such as a resonant cavity or waveguide [Gandhi et al., 1977]. The presence of objects in the field, such as other animals in the same cage, can also cause SAR variation in an individual animal due to scattering of energy by the other animals. Nose or mouth touching can induce hot spots at contact points due to high induced current between animals. Metal implants can cause intensification and modification of SAR patterns within tissue. Electric field intensification at the tip of a metal electrode is dependent on its length and diameter as well as the frequency of the RF field [NCRP, 1981]. For example, as a result, the presence of a thin metallic electrode in a cat brain for neurological recording increased the peak SAR 50 times [Johnson and Guy, 1972].

Time-Intensity Factors

External field intensity and exposure duration are important parameters that determine the total energy absorbed by tissues. When an RF field is amplitude or pulse modulated, SAR also varies with time. Therefore, measurement of the time-averaged SAR in itself is not adequate for exposure characterization; thus, the modulation characteristics must be specified when relating the SAR to any observed effect. Also, SARs vary with the animal's position when exposed to RF fields. Therefore, when an animal moves, the SARs change as a function of time. If an animal is restrained to keep the SAR constant, then an artifactual stress can severely contaminate the biological data. The SAR levels can be controlled within a relatively narrow range by exposing freely moving animals in cavities [Justesen and King, 1970] or in circularly polarized waveguides [Guy et al., 1979; Chou et al., 1992].

MEASUREMENT OF SAR

Localized (Single-Point) SAR

Implantable E-field probe. According to Equation 1, the SAR can be calculated from an induced E-field, tissue conductivity, and tissue density. An E-field can be measured at a point or points within a tissue-equivalent "phantom" model or a biological system by an implantable electric field probe. Tissue-equivalent materials have been developed by many researchers to simulate dielectric properties of biological tissues at frequencies of interest. Formulas and procedures for preparing tissue-equivalent fat, muscle, brain, and bone for RF application have been reported by Guy [1971], Bini et al. [1984], Chou et al. [1984b], Lagendijk and Nilsson [1985], and Hartsgrove et al. [1987]. These materials can be shaped to simulate the geometry of biological objects. The E-field

within an object can be mapped by moving a probe along a selected path. Implantable E-field probes provide the most sensitive and direct means of local SAR measurement. Probes with a dipole sensor length of less than 5 mm can detect SARs as low as 0.2 W/kg [Bassen et al., 1977; Stuchly et al., 1984; Bassen and Babij, 1990]. The sensitivity of an E-field probe is proportional to the length of the dipole (antenna) elements; the spatial resolution is inversely proportional to the length. Guy et al. [1987] and Chou et al. [1987] used a diode sensor, a microwave source modulated at 100% with a 1000 Hz square wave, and a standing wave ratio meter used as a voltage detector to increase the measurement sensitivity. SARs as low as 0.2 mW/kg were measured.

To measure the small E-field induced by a low-power RF source, such as a hand-held cellular telephone, sensitivity can be increased by the use of synchronous-detection or signal-averaging techniques. When the frequency decreases, spurious RF pickup in high-resistance leads significantly degrades resolution, which limits the use of currently available probes to frequencies above 150 MHz. The upper frequency is limited by the ratio of the RF wavelength in the tissue-equivalent material to the length of the dipole. The wavelength of an RF field in dielectric materials is approximately equal to the wavelength in air divided by the square root of the relative dielectric constant. Therefore, the internal wavelength is much shorter than the wavelength in free space. When the ratio of the wavelength in tissue material to the dipole length becomes approximately less than ten, the electric field is no longer sufficiently uniform over the length of the dipole to provide accurate results. This limits the use of commercially available probes when they are implanted in tissue-equivalent material to a few gigahertz (GHz). Practical E-field probes use three small orthogonal dipole antennas to provide isotropic measurements. Isotropic response of a probe is important whenever the polarization of an internal E-field is unknown (e.g., in curved or irregularly shaped biological objects). An implantable isotropic E-field probe is commercially available (Loral Microwave-Narda, Hauppauge, NY).

To determine SAR accurately using implantable E-field probes, the probes must be calibrated. The overall goal of any SAR calibration technique is to define SAR accurately within a specified tissue-equivalent model. For example, a slab or a spherical model can be used, provided that the SAR distribution is known and has been determined from classical theory. For calibration, the model should be large compared to the length of the probe sensors (dipoles), and the SAR should be uniform throughout its volume. Spherical or block models filled with tissue-equivalent material have been used by several researchers to calibrate implantable E-field probes [Bassen et al., 1977; Stuchly et al., 1984; Guy et al., 1987]. These models are irradiated by uniform microwave fields of a known strength and polarization. The voltage output from each of the probe's three orthogonal sensors is recorded during irradiation. Calibrations can also be performed in waveguides (a hollow rectangular or circular tube used for EM energy transmission at microwave frequencies) filled with tissue-equivalent liquids [Hill, 1982]. These calibration techniques are described in detail in the ANSI/IEEE C95.3-1992 measurement standard [ANSI/IEEE 1992b].

Cleveland and Athey [1989] used an implantable electric field probe with three orthogonal dipoles to study the SAR in a model of a human head consisting of simulated bone, muscle, eye, and brain tissue. The model was exposed to 810–820 MHz and 850–860 MHz fields emitted from 1.0 and 1.8 W hand-held radio transceivers. When the transceivers were held within 1 cm of the head, the maximal local SAR occurred in the eye or in other parts of the head, depending on the transceiver and the position of its antenna with respect to the head. The two highest SARs measured were 3.2 W/kg, which occurred at the surface of the eye at 810–820 MHz, and 3.5 W/kg, which occurred in the temple area at 850–860 MHz. Both values were normalized to a transmitter radiating 1.0 W. SAR peaks, as expected, were highly dependent on the relative position of the radios with respect to the head and the distance between the head and radiating structures.

Balzano et al. [1995] mapped the SAR in a model human head exposed to a 0.6 W cellular telephone operated at 835 MHz. They used a robot arm holding an implantable electric-field probe to scan the interior of a fiberglass skull filled with liquid material that had the dielectric properties of human brain. At 0.4 cm from the inside surface of the skull, the maximum SAR was 1.1 W/kg for a flip phone with the antenna extended, as shown in Figure 2. When the antenna was collapsed, the maximum SAR increased to 1.8 W/kg. In both cases, the maximum occurred near the lower portion of the ear, and the 1 gram averaged SAR was less than 1.6 W/kg, which is the peak value of the ANSI/IEEE C95.1-1992 SAR exclusion for the uncontrolled environment [ANSI/IEEE, 1992a]. Kuster et al. [1993] measured local SARs induced by 1.0 W European cellular phones operating at 890–915 MHz. When the telephone was held away from the face and the antenna was touching the occipital area of the head (worst-case exposure), the maximal SAR located within the model head was about 6.0 W/kg averaged over a volume of 1 cm^3 in brain-equivalent material.

Temperature probes. Because tissue temperature increases linearly during brief exposure to high-intensity RF radiation, the SAR can be obtained from temperature measurements as well. The maximal

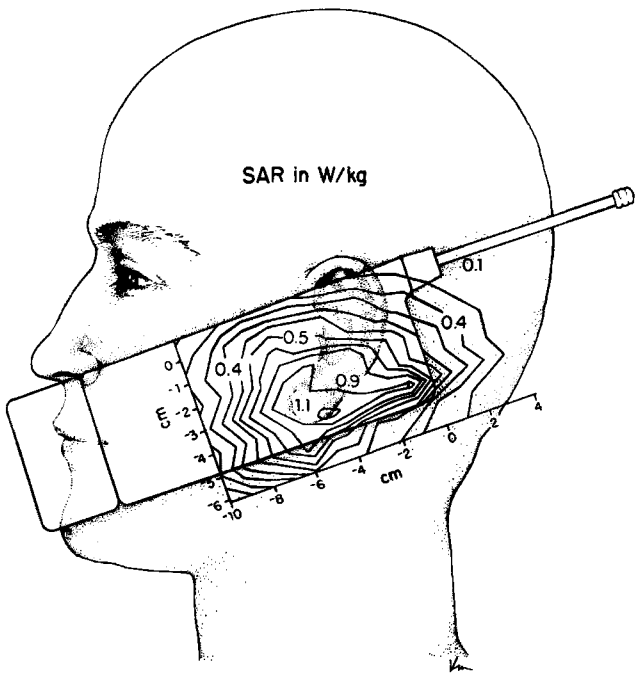

Fig. 2. Peak standard absorption rates (SARs) inside a human head exposed to a "flip" cellular telephone with the antenna extended [from Balzano et al., 1995].

temperature rise is usually kept below 10 °C to prevent increased tissue conductivity (approximately 2% per °C) from causing "thermal runaway." The runaway effect causes the hot area to absorb more RF energy than the cooler areas, and the hot area gets even hotter during the course of the exposure. In addition, even without thermal runaway, the changes in dielectric properties also alter the absorption patterns. Therefore, the high intensity exposure must be of short duration to minimize heat diffusion and to keep the maximal temperature rise at less than 10 °C.

Temperature measurement is the technique that is used most commonly for determining SAR in tissues and in in vitro culture systems. This does not imply that the mechanism for any observed biological effect is thermal in origin. Mittleman et al. [1941] were the first to quantify RF energy absorption by using temperature measurements. Initially, the unit W per liter was used, which was changed subsequently to W/kg by Cogan et al. [1958]. The relationship between SAR and temperature rise is

$$SAR \cong 4186 \frac{c_H \Delta T}{t} \quad (W/kg), \tag{5}$$

where c_H is the specific heat capacity of the tissues (kcal/kg· °C), 4186 is the conversion factor from kcal to joule, ΔT in °C is the temperature rise, and t is the exposure duration in seconds. The approximation symbol over the equal sign implies that accuracy is based on negligible energy loss by the irradiated body. Irradiation of the tissue-equivalent model must be performed at a high exposure level and short exposure duration to produce a measurable linear temperature rise. This must be done to allow accurate quantification of the rate of temperature rise in the absence of any significant thermal conductive loss. If these conditions are not fulfilled, then the SAR will be significantly underestimated.

A normalized SAR (W/kg per W input) is a convenient quantity. To calculate the actual SAR for low-power exposure, one simply multiplies the normalized SAR with the applied input power. For example, in one dosimetry study, an SAR in the brain of a rat carcass exposed at 300 W net input power to the exposure system was measured to be 60 W/kg. For a 0.5 W net power used in a biological study, the corresponding SAR in the rat brain is extrapolated to be $(60/300) \times 0.5 = 0.1$ W/kg. The temporal peak SAR in pulse-modulated RF exposures also can be calculated by dividing the average SAR by the duty factor. The duty factor is the ratio of pulse duration to the pulse period.

Mistakes have been made by investigators attempting to measure SAR in objects exposed to low power-density levels over long time periods. Removal of thermal energy via diffusion reduces the RF-induced temperature rise and greatly distorts the actual rate of energy absorption. In the case of living animals, the thermoregulatory effects of blood flow further reduce the accuracy of SAR measurements. Determination of the initial rate of a temperature rise is necessary to determine accurately the SAR.

Metallic temperature sensors, such as thermocouples and thermistors with metallic leads, cannot be used casually for temperature measurements in RF fields. The perturbation of the fields being measured by metallic sensors and wires prevents them from providing accurate data [Cetas, 1990]. EM fields also can induce interference in the electronic readout devices that are connected to temperature sensors via metallic wires. In addition, RF heating of metallic sensors and leads can produce erroneous SAR measurements. Shielding thermocouples or thermistors may minimize the interference problem, but it cannot solve the perturbation problem. Several microwave-transparent temperature probes have been available commercially for single-point measurement in biological bodies and exposure systems, but only two remain on the market. One is the Vitek-101 high-resistance-lead thermistor probe [Bowman, 1976], which is available from the BSD Company (Salt Lake City, UT). The carbon-loaded Teflon, high-resistance leads have electrical conductivity similar to that of biological tissues. Therefore, these leads do not disturb the field within the object. However, it must be noted that, when the leads

are exposed in air parallel to the electric field, induced current may heat the leads. The other probe is the Luxtron (Mountain View, CA) Model 3000 multi-channel fiber-optic thermometer [Wickersheim and Sun, 1987]. The sensors are made of temperature-sensitive phosphors, and the leads are plastic optical fibers. Up to 12 single- or multiple-array Luxtron sensors allow simultaneous SAR measurements at a number of locations in an exposed object. Multiple Vitek probes may also be used for this purpose.

Temperature probes may be used to determine the local SAR in a model of the head or body of a human only if sufficiently high RF power is radiated from the source. A spatial peak SAR of approximately 20 W/kg should be produced in a body or model to allow accurate measurements with temperature probes. Therefore, this sensitivity is far less than the 0.2 W/kg of commercial E-field probes. It is extremely difficult to use temperature to measure accurately the SAR delivered to a model of the human head by a low-power source, such as a hand-held radio [Balzano et al., 1978]. Guy and Chou [1986] constructed a high-power antenna and generated a field pattern similar to that of the original low-power mobile antenna and were able to provide enough RF energy to heat a model. Table 1 gives an example of the SARs measured by four Vitek 101 probes implanted in the model of a woman exposed to an RF field when it stood 9.5 cm away from a high-power, trunk-mounted, mobile antenna. The peak measured SAR of 0.147 W/kg per W input to the antenna occurred in the stomach region, 0.5 cm inside the model.

Planar (Two-Dimensional) SAR Measurements

The SAR distributions in biological objects or models are complex. Therefore, the single-point SAR measurement technique can be very tedious and time consuming for mapping the spatial distribution of local SAR throughout an object. Because dielectric properties vary with temperature, models or biological tissues must be cooled between exposures. Localized probing or mapping cannot guarantee that hot spots in the exposed subject have been located. Detailed mapping is necessary. To study the SAR pattern in a planar area within a three-dimensional volume, several methods have been explored. One simple method is the use of a temperature-sensitive liquid-crystal sheet. This method allows qualitative visualization of the temperature distribution on a surface. Leaving the liquid-crystal sheet sandwiched in a precut object during RF exposure can reveal an internal SAR pattern. However, the qualitative nature of this method limits its usefulness. Recently, Cristoforetti et al. [1993] reported the use of a CCD camera to convert the hue of liquid-crystal film color during heating to quantitative temperature data. Depending on the polarization of the E-field within the model, the presence of film can significantly affect the RF-induced current. This can result in an altered heating pattern, particularly when the film is perpendicular to the E-field within the model. The effect is also dependent on the frequency of the field.

Guy et al. [1968] developed a thermographic technique for the rapid measurement of SAR in an internal plane. A bisected mammal cadaver or model must be utilized. During RF exposure, the bisected halves are joined. After a brief high-power exposure, the halves are quickly separated, and the internal surface of one of the halves is immediately scanned by an infrared thermographic camera. Temperatures before and after the RF exposure are compared to determine the temperature elevations on the plane of interest. Depending on the resolution of the system, several hundred thousand points can be measured within seconds. The accuracy of this technique depends on the size of the animal or model, because heat loss between the time of exposure and the thermogram becomes relatively large for smaller objects.

Thermographic techniques have been used to determine the SAR distributions in human models standing near trunk- and roof-mounted mobile antennas similar to those used with cellular telephones [Guy and Chou, 1986]. Full-sized human models were filled with a high-water-content, simulated-muscle material and were exposed to an 835 MHz field from a mobile antenna (Fig. 3). Figures 4 and 5 show the SAR patterns in a woman model (sagittal plane) and in a child model (horizontal plane at the eye level), respectively.

Models may also be scaled [Guy et al., 1976]. With these models, far less RF energy is needed for SAR determination than for full-sized models. Consequently, the use of size-reduced (scaled) models is technically easier and is more economical. When a full-sized model is scaled down by a factor, the conductivity of the tissue-equivalent material and the RF

TABLE 1. Specific Absorption Rates (SARs) of a Standing Woman Exposed to a Trunk-Mounted Antenna (835 MHz) at 9.5 cm Distance*

	SAR (W/kg per W)			
Depth (cm)	Heart	Kidney	Liver	Stomach
0.5	.0207	.0746	.1170	.1470
1.0	.0260	.0642	.1100	.1350
2.0	.0121	.0307	.0540	.0727
3.0	.0092	.0171	.0289	.0381
4.0	.0042	.0074	.0148	.0189
5.0	.0026	.0034	.0076	.0084
6.0	.0014	.0025	.0039	.0040

*From Guy and Chou [1986].

Fig. 3. Photograph showing a full-sized woman model (sagittal one-half) exposed to high-power (10 kW) mobile antenna fields in an anechoic chamber for the quantification of energy absorption.

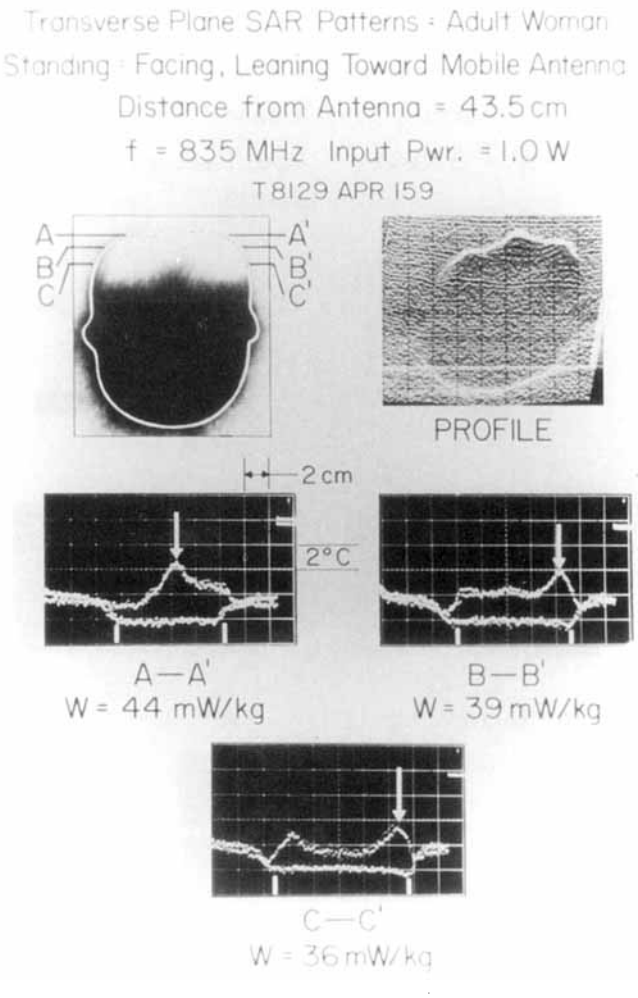

Fig. 4. Horizontal-plane SAR pattern at the eye level of a woman model exposed to 835 MHz UHF fields from a mobile antenna (43.5 cm distance, normalized to 1 W).

frequency must be increased by the same factor. These adjustments are made to preserve the same wavelength to body-size ratio. The final SAR measured in the scaled model also must be reduced by the same factor to represent the SAR that would be induced in a full-sized model. Scaling also allows a single-frequency RF generator to be used with different sizes of models to determine the SAR at a number of frequencies. This method has been used to obtain induced current densities in pig and man models exposed to 60 Hz fields. The results based on scaled models have been reported by Guy et al. [1976, 1982, 1984].

A new alternative to the thermographic method uses magnetic resonance imaging to obtain the heating pattern inside a model [Samulski et al., 1992]. This method would be desirable for noninvasive thermometry during hyperthermia treatment. However, the present cost of the procedure is too high to be practical for most applications. Recently, a luminescence imaging technique has been developed to map SAR distributions in optically transparent models [Bruno and Kiel, 1994]. The technique uses a chemiluminescent compound, diazoluminomelanin, and a quantitative luminescence imaging system to derive maps of the SAR distribution. This technique uses the phenomenon of changes in light intensity emitted by the chemical during RF exposure, and it is now under commercial development (Beam Tech Corporation, San Antonio, TX).

Whole-Body Averaged SAR

The whole-body averaged SAR in animals can be determined by twin-well calorimetry [Phillips et al., 1975; Blackman and Black, 1977; Allen and Hunt, 1979; Chou et al., 1984a]. Two animals of similar body mass are euthanatized and brought to temperature equilibrium. Then, one of the animals is exposed to an RF field.

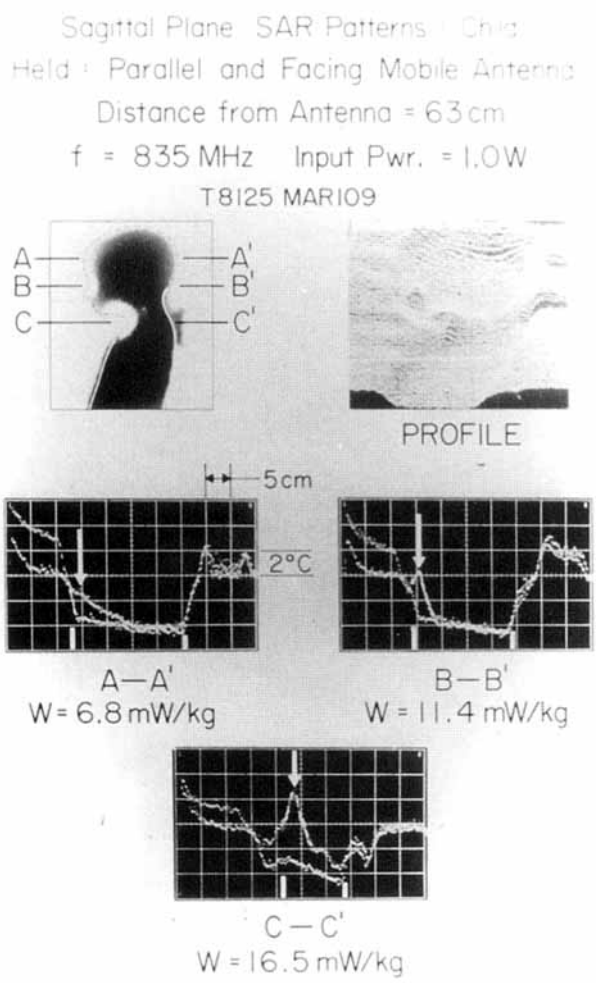

Fig. 5. Sagittal-plane SAR pattern of a child model exposed to 835 MHz UHF fields from a mobile antenna (63 cm distance, normalized to 1 W).

Immediately after exposure, the two carcasses are placed in a twin-well calorimeter. The whole-body averaged SAR in the exposed animal can be calculated from the heat differential between the two carcasses. In contrast to the thermographic technique that works well for large objects, twin-well calorimetry is a better method for small animals. The long heat diffusion time for large animals creates problems in twin-well calorimetry, because the animals lose heat so slowly that it may be several days before they reach an equilibrium temperature. During this time, decomposition of the cadaver generates additional heat that introduces errors in SAR measurements. Olsen and Griner [1989] have built a large calorimeter that can accommodate a full-sized human model. Scaled or full-sized models filled with tissue-equivalent material can be used to measure the whole-body averaged SAR. After exposure, the liquid is stirred to equalize the temperature throughout the medium, and the temperature rise measurement is obtained. The average SAR can be calculated by using Equation 5.

LIMITATIONS AND UNRESOLVED PROBLEMS OF SAR

Although SAR has been accepted world wide as a dosimetry unit and is the basis for national and international RF safety standards [NCRP, 1986; ANSI/IEEE, 1992a; IRPA, 1993; NRPB, 1993], there are limitations of its application in standard setting. The ANSI/IEEE C95.1-1992 standard [ANSI/IEEE, 1992a] specifies that the criteria for maximal permissible SARs for human exposure are applicable between 0.1 MHz and 6.0 GHz, i.e., a whole-body averaged SAR of 0.08 or 0.4 W/kg, depending on whether or not the person is aware of the exposure. At frequencies below 0.1 MHz, surface effects (shocks and burns) become issues. Research is needed on the dosimetric thresholds for both electrostimulation and energy deposition in the range of 0.01 to 1.0 MHz [Reilly, 1992]. The information is needed to shift from exposure limits based on electrostimulation at frequencies below 0.1 MHz to an energy-deposition criterion (SAR) above 0.1 MHz. At frequencies above 6 GHz, superficial power deposition (hence, external power densities) are more useful than the SAR produced within exposed tissues. Research is needed on heating of the human body above 6 GHz to verify both the transition from deeper deposition to surface absorption and the validity of the resulting short thermal time constants. Some mathematical analyses for planar surface heating yield thermal time constants of minutes. However, these results are questionable in view of the literature on IR surface heating [Foster et al., 1978]. Furthermore, the redistribution of thermal energy due to blood flow (convective) or conductive cooling must be taken into account.

The SAR limits in the ANSI/IEEE C95.1-1992 standard are based on reproducible SAR thresholds for disruption of learned behavior of laboratory animals accompanying whole-body RF exposure [de Lorge and Ezell, 1980: de Lorge 1984; ANSI/IEEE, 1992a]. Although there are few data corresponding to partial-body animal exposures, the present standard relaxes the SAR criterion for partial-body exposures of humans. In addition, the resulting energy induced in eyes and testes is limited more stringently than in other regions of the body. The application of C95.1 SAR limits to small volumes is an issue that needs more attention. For example, SAR measurements in 1 cm^3 volumes in heads have been performed in conjunction with cellular telephone dosimetric studies based on models. However, the biological effects of moderate duration exposures (e.g.,

30 min per day) of small volumes of brain tissues have not been documented adequately in terms of acute and chronic biological effects. Further dosimetric and biological effect studies on partial body exposures are needed, especially on the head. In medical applications of partial body exposure to diathermy or cancer hyperthermia, the SAR can be as high as 100 W/kg [Lehmann 1994].

It is important to continue performing experimental and theoretical research to improve the accuracy of data on the properties of biological tissues in RF fields. Recent reports by Gabriel [1995] indicate that live bone may have dielectric parameters that are closer to those of muscle, i.e., higher dielectric constant and conductivity, than have been assumed previously. These unresolved new data would suggest that an overestimation has occurred in brain SAR data in past dosimetric studies that used tissue-equivalent or computer models.

Unresolved issues in experimental dosimetry include the complexity and difficulty of performing SAR measurements. Higher uncertainties exist in experimental data obtained when the SAR values are small (less than 10 W/kg). This occurs when using low-power RF transmitters, such as hand-held wireless telephones. There is a lack of availability of complete calibrated, internal E-field measurement systems and sensitive (0.01 °C resolution), RF-transparent, temperature-probe systems. The internal E-field and temperature measurement systems that have been produced to date are relatively expensive and require a great deal of expertise and ancillary equipment. In addition, standard methods for calibrating E-field or temperature probes to an SAR reference standard do not exist. Finally, there is no commercial source for obtaining standardized models and tissue-equivalent materials, except on a costly, customized basis. This combination of factors points to a lack of consistent data from experimental SAR measurement systems and a tremendous dependence on the personal expertise of the dosimetric specialist.

The SAR is a scalar quantity. If the direction of the induced field or current is of importance to a biological effect, then the SAR cannot provide this information. In such a case, knowledge of the SAR alone would be inadequate, because it would not provide directional information. Furthermore, if an effect on biological cells or tissues is related to a direct interaction with the magnetic field (e.g., an interaction with magnetite), then the SAR concept is insufficient [Stuchly and Stuchly, 1986], and the exposure and dosimetric measurements would have to involve the internal magnetic field as well as the electric field. However, because the amount of magnetite in tissue is very small, the minuscule SAR component due to any magnetic field absorption would be difficult to measure.

It should be pointed out that the accuracy of SAR measurement by either an E-field probe or the temperature method is ±2-3 dB [Bassen and Babij, 1990]. The uncertainty is due to the steep gradients in induced field distribution and the thermodynamics of an RF-exposed biological body. The accuracy of the whole-body averaged SAR based on calorimetry is better, because it is within a few percentage points [Gandhi et al., 1979]. However, whole-body SAR is not suitable for dose-response evaluations of RF effects due to localized exposures of specific organ systems and regions of the body. Table 2 provides a list of some characteristics of RF dosimetry and its limitations.

DISCUSSION

Most of the research on RF exposure of animals has the ultimate goal of applying the results to risk assessment of human beings exposed to RF fields. Therefore, when effects are observed in experimental animals, there should be a way to extrapolate the effects to human beings [Michaelson and Lin, 1987]. Without quantification of EM field interaction with biological

TABLE 2. Characteristics of Radio Frequency (RF) Dosimetry

Whole-body averaged standard absorption rate (SAR)
Biological objects absorb RF energy at a higher whole-body averaged rate when they are exposed to a uniform E-field with the E vector aligned parallel to the long axis of the object
When a biological object moves with respect to an incident field, the whole-body average SAR can change by a factor of ten or more
Biological objects absorb maximal RF energy when they are exposed at their *resonant* frequencies; at the resonant frequency, the object length is 25–50% of the wavelength of the external exposure field
Local SAR
The highest local SAR is usually at or near the surface of an object exposed to an RF field
For curved surfaces and resonant objects, high SARs ("hot spots") may exist at various depths
Local SARs exceed the whole-body averaged SAR by 10–100 times. This ratio depends on the size of the local area over which the local SAR is averaged
The local SARs at various points in an immobilized biological object can be measured with an uncertainty of 10–30%
When the source of RF radiation is close to the biological object, the magnetic field may induce a higher maximal local SAR than the E-field
When a biological object changes its alignment with respect to an incident field, the local SAR at each point can change by a factor of two or more

tissues, it is impossible to make such an extrapolation and, thus, to predict safe exposure levels for human beings. Garn and Gabriel [1995] recently compiled results of 12 relevant publications concerning the relationship between external field strengths and the SAR inside the human body. The physical parameter termed SAR is now widely accepted by researchers in this field as a common unit for comparing biological effects of RF exposure. However, the techniques for measuring SARs are complicated and are not always reliable. Whole-body averaged SARs provide a first step in quantification of dose. However, planar or three-dimensional analysis of SAR and the spatial distribution of SAR in different tissues and body locations are also needed to make meaningful comparisons across animal species and to human beings. For example, the local SAR in the brain and spinal cord might be a more appropriate parameter for risk assessment than the whole-body SAR for relating animal studies of combined microwave and drug effects on behavior to human beings.

Although the SAR is not a thermal unit, exposure to RF fields transfers energy to the exposed object at a rate proportional to the exposure level. Therefore, it is important that the absolute temperature values and their distribution are thoroughly documented. This should be done during biological effects studies before, during, and after exposure of in vivo and in vitro subjects. During exposure of experimental animals or human beings, temperature distributions may equilibrate by means of physiological regulatory mechanisms. In in vitro exposures, thermal gradients and temperature distributions are especially critical. For example, temperatures in vitro might be controlled by a constant temperature bath. However, a monolayer of cells at the bottom of a culture dish may not be at the same temperature as that measured in the center of the culture medium.

When considering modulated, applied EM waves, the SAR should also be modified to reflect the time-varying nature of the RF field. For example, the perception of sound accompanying pulsed microwave exposure can occur for a single pulse [Lin, 1978; Chou et al., 1982]. It is improper to quantify this effect by using the SAR averaged over time. Instead, the calculation of SA for each pulse is a more suitable quantification. Another example of a modulation effect is the increase or decrease in Ca^{2+} efflux accompanying exposure to microwave radiation, which was reported by Bawin et al. [1975] and Blackman et al. [1985]. They found that the effect occurs only when the EM field is amplitude modulated, especially at 16 Hz. For this case, the 16 Hz modulation frequency also should be specified. Therefore, when specifying exposure parameters involving modulation, detailed information about the modulation (pulse width and repetition rate of a pulsed wave) should be provided. This is particularly important, because increasing numbers of pulse-modulated systems are being used (e.g., systems for the new generation of digital cellular telephones).

The relationship between the duration of exposure and any resulting biological effects in animals and the extrapolation of these data to humans is not trivial. Extrapolation of time requires knowledge of the mechanism of the biological effects. For example, the microwave auditory effect mentioned above has been shown to be caused by thermoelastic expansion of tissues for microwave pulses of less than 50 μs duration. The same exposure time can cause auditory perception in both rats and humans (different pitch due to the different cranium size), but the threshold intensities are different. The SAR does not imply a mechanism of effect; therefore, questions of thermal time constant, animal response time, and scaling of thermal effects are irrelevant.

CONCLUSIONS

Dosimetry is an important part of any scientific effort to assess the effects of RF fields on biological systems and species. During assessment, it is far better to use the SAR to quantify the RF fields within the object than to use only external field exposure data. Accurate determination of SAR is a complicated matter, even at a single frequency. Specialized physical measurements and computation can be used to determine approximate whole-body average and spatially localized SARs in a biological object. A significant amount of work must be performed to assess the SAR distribution in an object over a wide range of exposure frequencies. There are limitations on the rigor and completeness of SAR to define dose rate. However, despite the complexity, this should not be a deterrent to using SAR to quantify the biological effects of RF exposure and to develop RF guidelines. It is only with continued RF dosimetry research that the development of EM technology can be fostered safely for the benefit of mankind while avoiding unreasonable restrictions.

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