Published in final edited form as:

Phys Med Biol. 2003 July 07; 48(13): 2013–2022.

An alternative method for determination of low-frequency specific absorption rate patterns in homogeneous phantoms*

Brian B Beard and Isaac A Chang

Food and Drug Administration, Center for Devices and Radiological Health, Electrophysics Branch, HFZ-133, 9200 Corporate Boulevard, Rockville, MD 20850, USA

Abstract

We propose a new application of voltage gradient measurements to determine specific absorption rate (SAR) at low frequencies where quasi-static electromagnetic conditions apply. This method, which we call the voltage gradient method, relies on direct measurement of the voltage field rather than measurement of the electric field or thermal transients. The voltage gradient method is fast and can be implemented with voltmeters of moderate cost. We tested the voltage gradient method using normal saline, in a phantom with simple geometry, and a sine wave voltage source at 5, 10, 20 and 50 kHz. Compared to the SAR measured thermally in the same phantom, the voltage gradient method produced almost identical curves when normalized. When the results of the voltage gradient method were scaled to the same power level used for the thermal SAR, the agreement was compatible with typical thermal SAR accuracy.

1. Introduction

1.1. Specific absorption rate (SAR)

SAR has become the principal dosimetric parameter for measuring the absorption of electromagnetic energy in the human body. SAR is the mass-normalized rate of energy absorption, or dose rate, measured in real, or simulated, biological material. Its measurement is of particular interest for manufacturers of medical and wireless devices. The purpose of this paper is to describe an alternative method for measuring SAR at low frequencies where quasi-static electromagnetic conditions apply. Originally developed to quantify the transfer of external electromagnetic energy into the body, SAR can also be used to quantify energy deposition from sources internal to the body, such as medical implants. Existing standards for maximum exposure, and test methodologies, assume external electromagnetic fields; there are no published standards for electromagnetic sources internal to the human body. Consequently, the measurement of exposure from internal sources has been done on an *ad hoc* basis. If tissue ablation is the intent, the SAR pattern is needed. If neural stimulation is a concern, current density can be calculated from the SAR pattern via equation (1), where J is current density, σ is electrical conductivity and ρ is mass density,

*The opinions and conclusions stated in this paper are those of the authors and do not represent the official position of the United States Food and Drug Administration.

$$J = \sqrt{\sigma \rho (SAR)}. \quad (1)$$

The current ANSI/IEEE standard (ANSI/IEEE 1992) has two accepted methods for measuring SAR. The first uses electric field probes, the electric field method, and the second uses thermal probes, the thermal method.

1.2. The electric field method

The electric field method allows SAR to be computed using equation (2), where σ is electrical conductivity, ρ is mass density and $|\vec{E}|$ is the magnitude of the electric field vector,

$$SAR = \left(\frac{\sigma}{2\rho} \right) |\vec{E}|^2. \quad (2)$$

A typical electric field probe has three orthogonal dipole sensors. This arrangement is required to sense an arbitrarily oriented electric field vector. The magnitude of the electric field vector is computed as the square root of the sum of the squares of the three field components. The dipoles must be small, of the order of 5 mm, for acceptable spatial resolution. Because the dipoles are so small, their sensitivity falls off rapidly at longer wavelengths. The decreasing signal-to-noise ratio at low frequencies effectively limits the use of electric field probes to frequencies above 150 MHz (Chou *et al* 1996).

The dipole sensors in an electric field probe are closely spaced (<5 mm) but they do not measure the field components at the same point in space. Therefore, the spatial resolution of electric field probes is limited to the order of several millimetres.

Measurement systems using electric field probes must be calibrated precisely for sensitivity and isotropicity over the range of test frequencies. Electric field probe systems are expensive to acquire and maintain.

1.3. The thermal method

The thermal method allows the SAR to be calculated as shown in equation (3), where C_p is the specific heat of the tissue and (dT/dt) is the linear rate of temperature rise during a brief application of energy,

$$SAR = C_p \left(\frac{dT}{dt} \right). \quad (3)$$

In phantoms, the effects of thermal conduction and convection can obscure the linear rate of temperature change. In tissue, thermal conduction and blood flow have the same effects. Therefore, the energy applied must not only be for brief duration but also of large enough amplitude to produce a detectable increase in temperature. The lack of accuracy caused by

thermal conduction and convection and the requirement to use very high powers were motivations in the development of electric field probes (Bassen *et al* 1974).

Our interest in measuring SAR is to map the energy deposition patterns surrounding implanted medical devices that apply energy inside the body. SAR measurements in our laboratory are made in homogeneous liquid phantom media that simulate the conductivity of specific body tissues. The medical devices we tested deliver energy at frequencies below 500 kHz, mostly below 50 kHz. At these frequencies the electric field method is ineffective, so our only choice has been the thermal method. The SAR is measured using a thermal probe attached to a three-axis scanner. A high current amplifier provides brief (<1 s) pulses at powers up to several hundred watts. We have previously shown (Beard *et al* 2000) this system works well and is capable of providing accurate SAR measurements with high spatial resolution. However, we have encountered some difficulties stemming from the use of the thermal method.

Many of our test items experienced corrosion using the thermal method. This occurred in tungsten and stainless steel electrodes. Despite the use of charge balanced waveforms, the high current densities required to obtain a detectable rise in temperature caused visually noticeable corrosion.

When scanning a SAR pattern, each pulse of energy upsets the thermal equilibrium of the phantom. One must wait for convective flows to cease and the temperature to return to steady state before applying the next pulse of energy. High-resolution scans require thousands of individual energy pulses and often take days to complete, even for our computer-controlled system. It would be desirable to measure SAR at low frequencies without using high current densities and without long waits between measured points.

1.4. Computational models

It is also possible to calculate a SAR pattern from a computational model. However, properly modelling the electrical and anatomical geometry in three dimensions is a complex task. The very complexity of the model usually requires experimental data for verification, so laboratory measurement of SAR is still required. Also, software packages capable of this kind of modelling are expensive and time consuming to learn and run.

1.5. The voltage gradient method

We set out to develop a measurement technique for SAR that works at low frequencies, where the electric field method is ineffective, avoids corrosion, is quick, is reasonably accurate and does not require a large capital investment. To this end, we developed what we call the voltage gradient method. Temperature probes are used to measure SAR at low frequencies because electric field probes are not sensitive in this range, not because there is no electric field. Even at low frequencies, SAR is a function of the electric field, as shown in equation (2), and the electric field is related to the voltage (potential) field as shown in equation (4),

$$\vec{E} = -\nabla V = -\hat{i}\frac{\partial V}{\partial X} - \hat{j}\frac{\partial V}{\partial Y} - \hat{k}\frac{\partial V}{\partial Z}. \quad (4)$$

As shown in equation (5), it should be possible to calculate the electric field, and hence the SAR pattern, by computing the spatial gradient of a measured voltage field,

$$SAR = \left(\frac{\sigma}{2\rho}\right) |\vec{E}|^2 = \left(\frac{\sigma}{2\rho}\right) \left| \hat{i}\frac{\partial V}{\partial X} + \hat{j}\frac{\partial V}{\partial Y} + \hat{k}\frac{\partial V}{\partial Z} \right|^2. \quad (5)$$

The voltage gradient method is applicable at frequencies where electromagnetic conditions are quasi-static. An ac voltage field can be measured with a simple inexpensive equipment—an insulated probe and true-RMS voltmeter. A dc voltage field is not usable due to electrode polarization effects (Schwan and Ferris 1968). Because one is measuring voltage, and not temperature, there is no need to wait for thermal equilibrium between samples. Because heating is not necessary, the voltage amplitude can be reduced substantially which should reduce, or eliminate, corrosion. Further, unlike the electric field, voltage is a scalar field, so it can be measured using a single sensor with high spatial accuracy.

In theory, the voltage gradient method is faster, less expensive and less destructive than the thermal method. If the advantages of the voltage gradient method can be realized, while maintaining accuracy comparable to the thermal method, it will offer a viable alternative to the thermal method for low-frequency SAR measurements.

2. Materials and methods

We constructed a custom fixture to aid in validating the concept of the voltage gradient method. The fixture, diagrammed in figure 1, consists of a cylindrical copper tank with a ball electrode, made of stainless steel, in the centre. The metal rod supporting the ball electrode is heavily insulated. The ball electrode acts as an electrical point source and the copper tank as the ground. The tank is filled with liquid media that cover a removable copper screen placed 2.5 cm below the top of the tank. With the addition of the screen, the ball electrode is entirely surrounded by conductors at ground potential. A computer model of this simple geometry, with the origin at the centre of the ball electrode, shows a spherically symmetric voltage field within 5 cm of the ball electrode. Thus, on the line of points directly above the ball electrode, on the Z -axis, the voltage gradients in the X and Y directions are zero. Equation (4) then reduces to the one-dimensional problem shown in equation (6). A small hole in the screen, directly above the ball electrode, allows access for measurements,

$$SAR = \left(\frac{\sigma}{2\rho}\right) \left| \hat{k}\frac{\partial V}{\partial Z} \right|^2 = \left(\frac{\sigma}{2\rho}\right) \left(\frac{\partial V}{\partial Z} \right)^2. \quad (6)$$

An overview of the experimental apparatus is shown in figure 2. The positioning system has a spatial resolution of 0.0506 mm in all three axes. The voltage probe consists of a glass tube tapered to a hemispherical Pt/Ir (90/10) tip of 0.5 mm in diameter. The function generator is a HP33120A. Because the saline filled tank is low impedance, a current limiting resistor was placed inline with the ball electrode. The meters, both Keithley Model 197 microvolt digital multimeters, are capable of true-RMS voltage measurement from 20 Hz to 100 kHz. The first meter reads the actual voltage applied to the ball electrode (the source voltage). The second meter reads the voltage between the probe and ground. A GPIB interface connected the meters and function generator to the computer. A custom software program, written in Asyst, handled all positioning, instrument control and data acquisition.

When measuring SAR at RF frequencies, voltage pickup is always a potential source of error. Because our low-frequency apparatus used unshielded wire for all connections, we wanted to determine if voltage pickup, from the function generator or background sources, was a significant source of error. We took readings with the probe in the media and the function generator off, and with the probe in air above the tank and the function generator on. In all cases the probe voltage was low amplitude noise, at least 30 dB below the smallest signal recorded during the normal voltage gradient scans.

We also wanted to confirm that the voltage field in the tank was indeed spherically symmetric and undistorted by the ball electrode's support rod. An area along the side of the ball electrode was scanned from 2 cm below the ball to 2 cm above the ball. The plane of the scan passed through the centre of the ball and the axis of the support rod. The isopotential lines from this scan formed concentric spherical arcs that were identical above and below the height of the ball. This confirmed the field was spherically symmetric and undistorted by the support rod.

Twelve voltage gradient scans were made using three different liquid media and four different frequencies. The media used were 0 (deionized water), 0.01 and 0.155 molar NaCl solutions. The function generator was set to produce a sinusoidal output at 5, 10, 20 and 50 kHz. Following the voltage gradient scans, the apparatus was reconfigured for the thermal method as described in prior literature (Beard *et al* 2000, Mirotznik *et al* 1996). A thermal scan was performed using 0.155 molar NaCl solution. The less conductive solutions did not allow current densities high enough to produce significant heating. The scan was done at 60 Hz with a power setting of 34 W. A pre-scan linearity check showed a linear relationship ($r^2 = 0.9998$) between dT/dt and applied power from 1.4 to 52 W.

In all cases the area scanned, shown in figure 3, was identical. Data were taken at 1.01 mm spacing in the XZ plane producing an 11 by 41 array. The raw data arrays were processed using Matlab. Each array was filtered to reduce noise using Matlab's `wiener2` function with edge replacement. The three central columns of each array were averaged, by rows, to produce a single column vector, as shown in equation (7), where V is the data array and n is the row index (1–41),

$$\text{average_column_vector}(n) = \frac{[V(5, n) + V(6, n) + V(7, n)]}{3}. \quad (7)$$

The gradient of each average column vector was calculated with the Matlab gradient function, then squared and multiplied by $(\sigma/2\rho)$ to produce the SAR. For the thermal data, the average column vector was multiplied by the specific heat to produce the SAR.

3. Results

The average time required to perform a voltage gradient scan was 37 min. The thermal scan took 3 h and 10 min to complete with the same scanning system.

The voltage gradient scans using 0.0 and 0.01 molar NaCl were noisy and showed poor agreement across frequencies. Further, because the low conductivity of these solutions did not allow measurement of thermal SAR, there is no reference for comparison of these scans. Therefore, the only results presented will be those for 0.155 molar NaCl solution.

Figure 4 compares the results for the thermal SAR with those from the computer model for the same NaCl solution and source voltage. Because the voltage gradient and thermal data were collected with different source voltages, the absolute SAR in each pattern will differ. By normalizing each SAR pattern to its maximum, their shapes can be compared. Figure 5 shows the normalized data for the voltage gradient scans using 0.155 molar NaCl at 5, 10, 20 and 50 kHz. Figure 6 shows the curves for the voltage gradient scans versus the thermal scan.

According to equations (4) and (5), if the source voltage is increased by a constant K , then the resultant SAR should increase by K^2 . This is only true if the test geometry is constant and non-linear effects are excluded. Table 1 lists the source voltages for the voltage gradient scans and the scaling factors (K^2) used to scale the voltage gradient scans to the power level of the thermal scan. Figure 7 plots the scaled SAR patterns for the voltage gradient scans with the thermal SAR. Figure 8 plots the difference between each scaled voltage gradient SAR and the thermal SAR as a percentage of the thermal SAR.

The same stainless steel ball electrode was used for all the voltage gradient scans. It was then removed from the threaded support rod and replaced by an identical electrode. The second electrode was used for the thermal linearity check and the thermal SAR scan. To compare corrosion, the second electrode was removed and photographed next to the first electrode (figure 9).

4. Discussion

We found the time required for a voltage gradient scan to be less than one-fifth that required for a thermal scan. This could be improved slightly by replacing our voltmeters, rated at 3 readings per second, with faster meters rated at more than 30 readings per second. It is clear

that the voltage gradient method can acquire SAR measurements faster than the thermal method.

The stainless steel ball electrode used for the thermal SAR measurement was completely covered in corrosion, whereas the stainless steel ball electrode used for all 12 voltage gradient scans showed no evidence of corrosion. This indicates that the voltage gradient method is less destructive than the thermal method.

The normalized SAR patterns shown in figure 6 illustrate that the shape of the voltage gradient SAR is close to that found with the thermal method. However, the reason one makes SAR measurements is to estimate exposure under conditions of actual use. Therefore, one must have some means of scaling the patterns to the proper magnitude. When the actual source voltage is known, the voltage gradient results can be scaled to the proper magnitude as shown in figure 7 and table 1. As shown in figure 8, these scaled results are quite close to the thermal SAR, slightly exceeding it where the SAR is high. It is well known that the thermal method tends to underestimate the SAR, particularly in liquid media, due to rapid thermal diffusion (Chou *et al* 1996). Therefore, the difference in magnitude is consistent with the expected accuracy of the thermal method. The voltage gradient SAR pattern could also be scaled using a few thermal SAR measurements at identical spatial coordinates.

We conclude that the voltage gradient method is capable of accurate SAR measurements. To produce accurate results, the voltage field should be sampled densely. Because computation of the gradient is a differential process, it enhances noise, as opposed to an integral process that suppresses noise. Therefore, the voltage data should be lowpass filtered before computing the gradient.

We plan to acquire true RMS voltmeters with a broader frequency range so that we can verify the voltage gradient method at higher frequencies. We also plan comparisons using more complex geometries.

References

- ANSI/IEEE. IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave (ANSI/IEEE C95.3–1992). Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc; 1992.
- Bassen HI, Swicord M, Abita J. A miniature broadband electric field probe. *Ann New York Acad Sci.* 1974; 247:481–93.
- Beard BB, Mirotznik MS, Chang IA. High spatial resolution measurements of specific absorption rate around ICD leads. *Med Eng Phys.* 2000; 22:587–92. [PubMed: 11182583]
- Chou CK, Bassen H, Osepchuk J, Balzano Q, Peterson R, Meltz M, Cleveland R, Lin JC, Heynick L. Radio frequency electromagnetic exposure: tutorial review on experimental dosimetry. *Bioelectromagnetics.* 1996; 17:195–208. [PubMed: 8809359]
- Mirotznik M, Cheever E, Foster KR. High-resolution measurements of the specific absorption rate produced by small antennas in lossy media. *IEEE Trans Instrum Meas.* 1996; 45:754–6.
- Schwan HP, Ferris CD. Four-electrode null techniques for impedance measurement with high resolution. *Am Inst Phys.* 1968; 39:481–5.

Figure 1.
The test tank designed for this experiment: (a) is a side view and (b) is a top view looking down through the copper screen.

Figure 2.
Block diagram overview of instrumentation system.

Figure 3.
This planar area, directly above the ball electrode, was measured for all reported scans.

Figure 4.

The SAR results from the thermal scan and computer modelling using 0.155 molar NaCl and source voltage of 21.5 V.

Figure 5.
The normalized SAR data from the voltage gradient scans using 0.155 molar NaCl at 5, 10, 20 and 50 kHz.

Figure 6. Normalized SAR data from the voltage gradient scans in figure 4 with the normalized thermal scan data.

Figure 7.
The thermal SAR data and the voltage gradient SAR data scaled to the power used for the thermal scan.

Figure 8.

The difference in SAR between each of the four voltage gradient scans and the thermal scan, expressed as a percentage of the thermal SAR.

Figure 9.
The image on the left is the stainless steel ball electrode used for all the voltage gradient scans. The image on the right is the stainless steel ball electrode used for the thermal scan.

Table 1

The source voltage for each of the voltage gradient scans. The scaling factor is the square of the ratio of the mean thermal source voltage (21.5 V) to the mean voltage gradient source voltage.

Frequency (kHz)	Mean voltage gradient source voltage (V_{rms})	Scaling factor (K^2)
5	0.3071	4901
10	0.2844	5715
20	0.2682	6426
50	0.2569	7004