SAR?

Hubert Trzaska

EM Environment Protection Lab., Techn.Univ. of Wroclaw, Poland
Wyspianskiego 27, 50-370 Wroclaw, Poland

Abstract
The paper discusses several aspects of the practical application of the SAR. It is shown that the unit is an ideal solution for basic research and laboratory experiments. SAR is directly nonmeasurable unit. Although methods and devices based upon indirect SAR measurements may widen our knowledge about EM energy distribution and absorption within a body. It is shown that for practical applications the temperature SAR measurement methods are not sensitive enough while methods based upon E (H) measurement are less accurate than traditional approaches. As a result of assumption SAR = 4 W/kg as a basic restriction the present protection standards are illogical and nonrealiazable. A return to traditional units (E,H,S) in the standards and surveying metrology is suggested.

Introduction

Specific Absorption Rate (SAR) has been widely accepted as an indicator of the ElectroMagnetic (EM) energy absorption by a living organism and among others, due to it, it was assumed as a good baseground for many protection standards and SAR was introduced to them as the basic restriction. Two introductory remarks:
- SAR is almost ideal unit showing quantity of energy absorbed from the electromagnetic field (EMF),
- the magnitude of SAR is a function of parameters characterising the EMF (frequency, modulation, polarization), the exposure conditions (temperature, humidity) and individual properties of the exposed animal or person (fatness, psychophysiological status, effectiveness of the thermoregulation system).

Evident conclusion:
- SAR may be excellent measure of correlation between exposure and thermal effects caused by it,
- the magnitude of the SAR, assumed as permissible, is a result of conditions in which experiments were carried out, thus: the magnitudes suggested by different authors erformed in different conditions, differ more than in one order of magnitude [1].

As a result of a compromise, in famous paper [2] as the basic restriction was accepted SAR = 4 W/kg, that is approximately equal to the geometric mean of the magnitudes given in the literature. The compromise is here evident because for a standard formulation an introductory level assumption was necessary. However, it well illustrates that the assumed SAR, and the basic restriction, is not a physical constant but a magnitude chosen in more or less arbitrary way thus: approach to it should be flexible.

Tutorial digression

Lets imagine two identical parallel plates of surface area S [m^2] placed at distance d [m]. Between the plates is immersed a lossy medium that occupies full volume between the plates, and to the plates is applied voltage V [V] as shown in Fig.1.

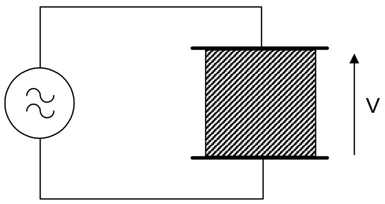

Fig.1 A lossy medium between two plates.

The set shown in Fig1 is a typical one in analysis of the effectiveness of dielectric heating. The power P [W] absorbed in the medium is:

$$P = VI\cos\varphi \approx VI\text{tg}\delta \quad 1.$$

where: I - current flowing through the medium [A]:

$$I = V\omega C$$

φ - phase shift between V and I,

δ - dielectric loss angle:

$$\delta = 90 - \varphi$$

ω - angular frequency,

C - capacitance of the set [F]:

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d}$$

ε_0 - permittivity of the vacuum [F/m],

ε_r - relative permittivity.

The energy W [Ws], absorbed in the medium, we'll get multiplying power, as given by formula (1) by time of exposure t [s]. Taking into account above relations we may write:

$$W = Pt = \omega\varepsilon_0\varepsilon_r vE^2 t\text{tg}\delta \quad 2.$$

where: E - electric field intensity [V/m]:

$$E = \frac{V}{d}$$

v - volume of the medium, v = Sd.

The energy W is transferred into heat Q [J], that may be expressed in the form:

$$Q = cv\rho\Delta T \quad 3.$$

where: c - specific heat of the medium [J/kgK],

ρ - mass density [kg/m^3],

ΔT - temperature increase [K].

If we assume that in the system no energy transfer into surrounding, i.e. we'll neglect the energy losses the energy W must be equal to the heat Q. It allows a comparison of the magnitudes given by formulas 1 and 2 and then calculation t, it gives:

$$t = \frac{\rho c\Delta T}{\varepsilon_0\varepsilon_r\omega E^2 \text{tg}\delta} \quad 4.$$

An interpretation of the formula may be as follows: what a time is necessary to increase temperature of a medium, characterized by it's parameters, in ΔT while exposed to E-field at angular frequency ω. The formula is plotted in Fig.2 for following parameters:

ρ = 1000 kg/m^3,

c = 2000 J/kgK,

ε_r = 5,

tg δ = 0.1,

ΔT = 0.01 K.

Properties of the biological medium were taken from [3] and ΔT was assumed as declared resolution of the best class thermometers.

SAR

While we accept any doubtless advantages of the SAR as the unit applied in the basic research, lets analyse its applicability for practical purposes.

The SAR is defined twofold:

1. as a measure of the temperature increase of exposed object:

$$SAR = \frac{c\Delta T}{t} \quad 5.$$

SAR ?

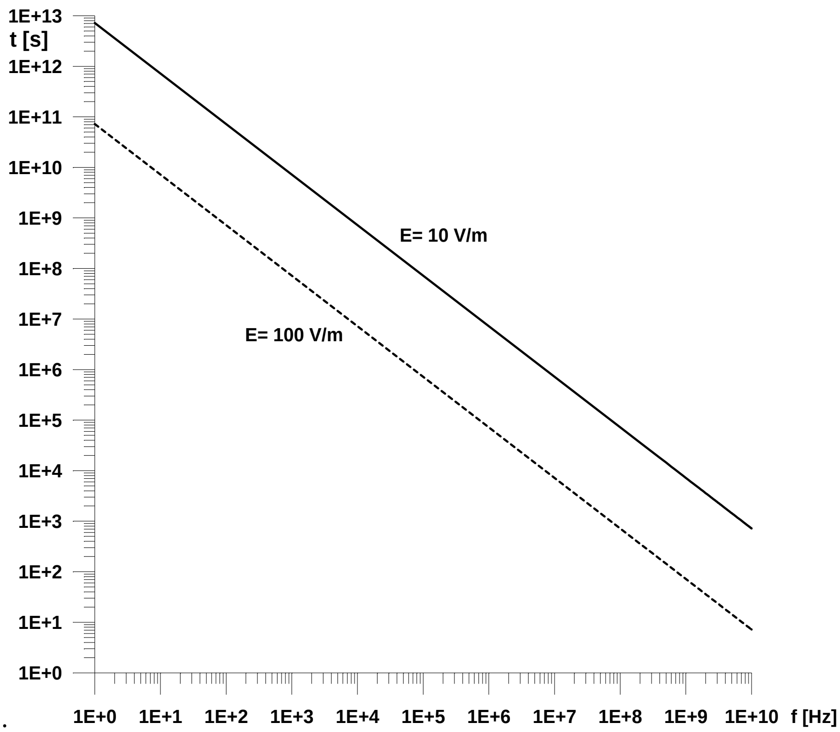

Fig.2 Heating time versus frequency for E = 10 and 100 V/m

2. as a measure of EMF energy absorption:

$$SAR = \frac{\sigma E^2}{\rho} \qquad 6.$$

where: σ - conductivity [S/m],
other indications as above.

Definition 1 creates some doubts as regards as to the possibility to measure the temperature increase inside a living organism in which correctly acts a thermoregulation system (even not to mention a problem of noninvasive access to points in which the temperature should be measured). Apart from it the definition allows to design an almost ideal measuring device for the absorbed energy measurement: we may construct an anthropoidal phantom, the electric properties of which would reflect that of the original object, and with the use of temperature sensors, connected to a measuring device with the use of transparent leads, we would be able to measure temperature distribution inside the phantom. Almost ideal dosimetric solution! We may add that the measurement with the use of the phantom will be independent of the exposure conditions and the local circumstances - they will be very similar in the case of the phantom and in the case of a person exposed in the same conditions with an accuracy limited to the phantom design. Of course, an error will appear due to less energy dispersion in the latter case as a result of the thermoregulation *in vivo*, moreover such a device will be somewhat cumbersome in the case of surveying measurements, performed outside of laboratory conditions. With no regard to it the device assures almost complete information upon absorbed energy and it's distribution in the object. The use of photonic techniques allows full spectral and phase information conservation. Unfortunately, its basic disadvantage is its sensitivity that eliminates almost completely the device from practical applications. The case was discussed above and it confirms the conclusion. Although the exposition conditions in the estimations were taken almost as a rabbit from a hut, however, a difference even on the level of one order of magnitude or more does not change the above conclusion.
Lets make here another digression. The both definitions of the SAR should be equivalent. It allows us to compare them:

$$\frac{\sigma E^2}{\rho} = \frac{c\Delta T}{t} \qquad 7.$$

or calculating t we have:

$$t = \frac{c\rho\Delta T}{\sigma E^2} \qquad 8.$$

Making simple substitution:

$$\sigma = \varepsilon_0 \varepsilon_r \omega \mathrm{tg}\delta \qquad 9.$$

we have identical dependence as given by formula 4. It confirms that the definitions of the SAR were introduced in simple mechanistic way, similar as formula 4. It does not reflect any personal properties, field configuration, heat exchange, etc.

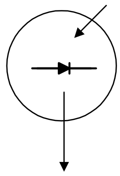

Fig.3. A concept of the “SAR probe”

Definition 2 is irreplaceable in numerical dosimetry. Depending upon accepted model it allows precise estimation of energy absorbed in arbitrary chosen point of a body, localizing hot spots and the energy distribution in the whole body. However, the use of the definition for measuring purposes is loaded with significant error resulting from the accepted method. Lets start from the statement that the SAR is a nonmeasurable unit. The subject of the measurement is E. In order to nearer the measuring conditions to the real ones an E-field sensor is immersed in a sphere filled with a medium that parameters are selected similar to the real properties of a living body, as shown in Fig.3.
The approach is loaded with remarkable error resulted, among others, from:
- different propagation properties of small sphere in relation to real dimensions of a body and different frequency dependence of absorption; the absorption is a function of polarization (it is different for different spatial EMF components), reflection, refraction and wave type (plane-wave, spherical- or cylindrical one) wave zone (induction, near- or far-field),
- a choice of the electric parameters of the medium is almost an arbitrary decision and it does not reflect complex structure of living body, different parameters of the same organs and tissues at different men, different shapes, weight, metabolism, thermoregulation or even way of life of the person that should be represented by the probe.
Thus: an estimation of an error of the equivalence of the SAR measured this way and the real magnitude of the SAR in a real body shows values on the level of one order of magnitude or worse.

There is another possibility: traditional measurement of E (H) in a place and then calculate SAR. The approach may be characterized with the use of an old quip about "scientific method" consists in "scratch behind right ear with the left hand". Another words: the use of the worst way. Not to add that the method is loaded by much larger error than the E (H) field measurement. The factors limiting accuracy of the procedure are similar as above, and they depend upon the field characteristics, propagation phenomena, personal properties of a person, etc.

Protection standards

By many bodies the mentioned magnitude SAR = 4 W/kg was assumed as "a dogmatic physical constant" and, as a result, it became a starting point for formulation of national and international protection standards. In order to have quasicontinuous dependence between the permitted exposure and frequency in the standards preparation were made strange attempts. Their result may be seen in the form of innovative selection of frequency ranges, baseless frequency dependencies (square, square root, 1.668), precisely given exposition levels and many others [4]. It has lead to standards that are illogical and nonrealizable.
1. Logic
Figures given in the standards are sometimes precised with accuracy to the forth significant number. It would suggest that we know biophysical phenomena with the same accuracy. As it was already mentioned the literature gives magnitudes of the SAR within frames 1-20 W/kg. Thus final results (standards) given with accuracy better than introductory data (exposure levels) are illogical.
2. Realization
Not to mention that the SAR is nonmeasurable it should be remind that the accuracy of the best EMF meters, designated for the far field measurements, does not exceed 1 dB. Metrological correctness suggests that a measured magnitude should be measured with accuracy to the last significant figure. It would require a meter

that would assure accuracy on the level 0.01%. In our case it is a pure nonsense as the best EMF standards are on the level of 5% while a standardized device cannot be more accurate than the standard applied to calibrate it. The case may be reduced ad absurdum if take to account these frequency ranges in which exposure is a function of frequency. As frequency may be measured with accuracy better than 10E-10 it would suggest necessity of EMF measurement with similar accuracy.
The procedure applied for the safety levels selection, i.e.:

bio-medical investigations – SAR – a safety factor – model analyses – exposure levels

is fully correct. However, every step in the procedure is loaded with a specific error. If we remember it, it allows more flexible approach to the final result of the procedure and establishing such a standard that would be logical, realizable and friendly for it's users. An example of the possible here solution is shown in Table 1 for the case of the professional exposure levels.

Table 1. An example of permissible professional exposure

Frequency range [MHz]	E-field [V/m]	H-field [A/m]	Power density (S) W/m^2
0.003-0.1	600	160	
0.1-3	600	16/f	
3-30	1800/f	16/f	
30-100	60	16/f	
100-300	60	0.16	
300-300000			10

Of course, exposures given in the table are only an example of possibility and nothing more. It is possible to generate several simple examples, however, their final shape should be prepared by biologists and medical doctors, not by engineers or physicists; the latter represent a tendency to formal perfection, and the results of it we have as the present standards.

Summary

The paper discusses in details disadvantages of the practical applications of the SAR. It shows necessity to return in practice to the use of E, H, S and I, and on the ground the paper shows failures of the European and US protection standards. SAR should be accepted as an ideal unit for basic laboratory studies (as technical as well as biomedical) while its use as a practical unit should be limited and it may be accepted as a basic restriction in the protection standards, however, it's role should be only auxiliary one in the way to formulate the permissible exposure levels. The use of traditional units in EMF surveying and out-the-lab EMF measurements is much more convenient and, the last but not the least, more accurate as compare to the SAR procedures.

References

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