Introduction to electromagnetic dosimetry: the assessment of dosimetric quantities in exposed subjects

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Contents

1. Electromagnetic dosimetry

Electromagnetic dosimetry is a technical-scientific discipline that studies the coupling mechanisms between an electromagnetic field and a biological object immersed in it or, as it is usually said, "exposed" to it.

Coupling is the first of a chain of interlinked biophysical phenomena through which the interaction between an electromagnetic field and a biological object takes place, and which schematically comprises the following steps.

1. **Exposure**: a biological object is immersed in an electromagnetic field.
2. **Coupling**: the electromagnetic field induces certain physical phenomena, characterised by specific physical quantities, in the tissues of the exposed organism; these phenomena originate from the action of the field forces on the electric charges and currents present in the tissues.
3. **Biological effect**: the physical phenomena induced by the external field always cause a deviation from the conditions of electrical equilibrium at the molecular level; however, to properly speak of a biological effect, a morphological or functional change must occur in higher-level structures (tissues, organs or systems).
4. **Biological or health damage**: a biological effect does not necessarily constitute damage; for damage to occur, the effect must exceed the compensation capability available to the organism, which also depends on environmental conditions.

In this chain of events, dosimetry sits, as mentioned, at step 2). It aims at determining the physical laws that establish the relationship between the intensity of the external fields and the value of the physical quantities — which in the following we shall call "dosimetric quantities" — induced in the tissues. Although the whole interaction process between an electromagnetic field and a biological organism is clearly multidisciplinary (as it involves physics, biology and medicine), the coupling proper and the dosimetry that studies its mechanisms quantitatively are genuinely physical disciplines.

1.1 Basic dosimetric quantities

The most authoritative international standardisation bodies and the vast majority of the scientific community dealing with the interaction between electromagnetic fields and biological systems agree in recognising that the biological effects of electromagnetic fields are determined by a few fundamental physical quantities or, at the very least, that these quantities are the most suitable to correlate the exposure intensity with the magnitude of the observed effects, and therefore to describe the latter quantitatively. We shall call these quantities "basic dosimetric quantities"; the terms "primary quantities" or "fundamental quantities" are sometimes used as well. In the ICNIRP guidelines [1] and in the European Recommendation that adopts them for the protection of the general public [2], the corresponding limit values (i.e. the maximum values

that the basic quantities must not exceed in the tissues of the exposed organisms) are called "basic restrictions", whereas the European Directive on occupational exposure [3] uses the term "exposure limit values".

For frequencies up to a few hundred kilohertz, the basic dosimetric quantity is the internal electric field E_i (V/m) induced by the fields in the tissues of the exposed organism, while at higher frequencies it is more appropriate to refer to the specific absorption rate SAR (W/kg), given by the electromagnetic power dissipated in the tissues per unit mass. The two quantities are obviously related, since it is easily seen that:

$$\mathrm{SAR} = \frac{\sigma E_i^2}{\delta} \qquad \text{(Eq. 1)}$$

where σ (A/Vm) and ρ (kg/m³) are respectively the electrical conductivity and the density of the biological material involved.

Electromagnetic dosimetry aims at quantitatively determining the magnitude of the basic dosimetric quantities, once both the distribution of the impressed electromagnetic field in which the biological organism is immersed and the conditions under which the exposure takes place are known. The latter include the morphological and electromagnetic characteristics of the exposed organism, its posture, as well as the geometrical structure and the electromagnetic characteristics of all the objects present in the so-called exposure scenario, i.e. the environment where the exposure occurs. To achieve its goal, electromagnetic dosimetry can make use of experimental, analytical and numerical methods. Experimental dosimetry relies on instrumentation and measurements, analytical dosimetry seeks the direct solution of the coupling equations, and finally numerical dosimetry uses numerical solution techniques based on the use of computers.

1.2 Dosimetry and standards

All the most authoritative international standards specify, alongside the maximum admissible limits for the basic quantities, limit values for the intensities of the external fields as well. ICNIRP [1] and the European Recommendation [2] call these values "reference levels", whereas the European Directive [3] uses the term "action values". In both cases, these are the root-mean-square (RMS) values of the unperturbed electric and magnetic field intensities, i.e. those measured in the actual exposure scenario, at the exact spot where the exposed subject will be, but without the subject being present. The usefulness of the reference levels is evident, considering that the basic quantities are not directly measurable in the exposed subject and that, therefore, compliance with the basic restrictions cannot be directly verified in a simple way.

While the basic restrictions are established with direct reference to the biological effects (interposing appropriate safety margins), the standards use the results of the most accredited dosimetric models to derive the reference levels from those restrictions. Such models refer to standardised and suitably conservative exposure situations, so that compliance with the reference levels can reasonably be deemed to guarantee compliance with the basic restrictions, thus providing ample protection against the effects the standard is meant to guard against. The

converse is not true, though: there may be cases where the reference levels are exceeded without this necessarily implying that the basic restrictions are violated. Since it is the latter that ultimately carry biological significance, the standards generally allow the reference levels to be exceeded, provided it can be demonstrated that the basic restrictions are not violated.

From the above it is therefore evident that the study of dosimetry — besides being important from the standpoint of knowledge — also has considerable applicative interest. Indeed, the drafters of the standards use the results of dosimetric studies to establish the relationships between basic restrictions and reference levels, while those who apply the standards may find themselves having to use the dosimetric models directly, to verify whether, in the particular exposure situation under consideration, the basic restrictions are met even though the reference levels are exceeded.

2. Experimental dosimetry

Experimental dosimetry uses dedicated instrumentation to measure the dosimetric quantities directly in the exposed subject or in an artificial model thereof.

The in-vivo measurement of the basic dosimetric quantities (internal electric field or SAR) requires inserting specific probes inside the exposed tissues. As can easily be imagined, such a measurement is far too invasive to be carried out on a human organism, whether for experimental purposes or — all the more so — for exposure control. Moreover, measurements on laboratory animals are not much used either, mainly because of the difficulty of extending the acquired results to humans. Experimental dosimetry is therefore mostly devoted to:

- non-invasive in-vivo measurements of derived quantities (mainly, as we shall see, the induced current);
- invasive measurements of basic dosimetric quantities in synthetic "phantoms".

2.1 Induced current measurements

The current induced in an organism can also be measured by non-invasive means. In particular, it is possible to measure the total induced current or the current induced in a limb. It should be remembered that, strictly speaking, induced current measurements are not true dosimetric measurements, since the induced current is not a basic dosimetric quantity. Indeed, the aforementioned international standards do not set exposure limit values on induced currents, but rather action values intended to prevent the local SAR limit in the limbs from being exceeded under particular exposure conditions.

The total induced current flowing to ground through the feet of an exposed subject can be measured by means of dedicated devices, also commercially available, known as "stand-on sensors". These devices consist of a sort of platform formed by two (roughly square) horizontal plates placed one on top of the other and electrically connected by a calibrated impedance. The subject stands on the upper plate, while the lower plate is in contact with the ground, so that the calibrated impedance ends up in series with the current path; the current can then be

determined from the measurement of the radiofrequency voltage developed across the impedance itself. Stand-on sensors suffer from some problems that occasionally make their use troublesome. For instance, in some cases they may overestimate the measurement, if the external electric field induces charge directly on the surface of the probe, giving rise to a current that improperly contributes to the measured value. In other cases, stand-on sensors may instead underestimate the measurement, if parts of the subject couple directly to ground, thus originating a current that does not pass through the probe and is therefore not measured. See the references [4,5] for applications and results.

The current induced in a limb (arm or leg) can be measured by means of ammeter devices (also of commercial type) operating on the current-transformer principle [6] and known as "clamp-on sensors". Devices of this type offer clear advantages over the platform ones: besides greater measurement reliability and accuracy, they allow the subject to keep working, walking or climbing stairs during the measurement, which is therefore generally performed under more realistic conditions.

All these devices typically have a flat frequency response from a few kilohertz up to about one hundred megahertz.

2.2 Measurements on phantoms

As an alternative to the in-vivo measurements of the induced current (which, as mentioned, is a derived quantity), measurements of basic dosimetric quantities can be performed on phantoms.

For the internal electric field, miniaturised dipole probes of various designs are generally used: the detected electric field is given by the ratio between the potential difference measured by the dipole and the distance between its two electrodes.

Probes of this type can be of the direct-detection kind or with a non-detected sensor (i.e. AC-coupled to its measuring instrument). The latter can only be used at the lowest frequencies (from 50 Hz to about ten kilohertz), since at higher frequencies various difficulties come into play (noise, insufficient common-mode rejection, contact impedance, electrode polarisation) that make the measurement troublesome, inaccurate and unreliable; some of these difficulties, and others as well, are discussed in [7,8]. At the higher frequencies (from about ten megahertz upwards), measurements on phantoms can advantageously be carried out using direct-detection probes instead, which integrate a dipole sensor and a semiconductor-diode detector to provide the meter with a DC signal.

For SAR measurements, similar sensors can be used (the SAR being related to the internal electric field through Eq. 1), or thermometric devices, with which the SAR itself is deduced from the initial rise of the local temperature that the dissipated power produces in the exposed material; indeed, as long as heat diffusion phenomena are negligible, it obviously holds:

$$\mathrm{SAR} = c\frac{\Delta T}{\Delta t} \qquad \text{(Eq. 2)}$$

where c (J/kg°C) is the specific heat of the material involved, while ΔT is the temperature rise occurring in the time interval Δt during the initial phase of the heating. In practice, the sensors used can be implantable miniaturised thermometers, of the thermocouple or thermistor type, or infrared thermal cameras, or even thermochromic liquid-crystal sheets that show the temperature reached by means of different colours.

The phantoms used for these measurements are artificial simulators of biological organisms, made of synthetic materials suitably designed to provide dielectric characteristics similar to those of organic tissues. All the measurement techniques mentioned (with the sole exception of the one based on the use of a thermal camera) require that probes can be inserted into the phantom and therefore need liquid or semi-liquid phantoms, which impose severe limitations on the possibility of building complex models that are realistic both in shape and in composition. Furthermore, the techniques based on thermal cameras or thermochromic liquid-crystal sheets require transparent phantoms, or that the phantom itself can be quickly opened and analysed after the exposure.

3. Analytical dosimetry

Analytical dosimetry (also called "theoretical") is based on the direct solution of the equations describing the coupling of the electromagnetic field with the exposed organism and the surrounding environment.

Put very concisely, it is a matter of setting up and solving a system of Maxwell equations that account for the emission characteristics of the sources and for the geometrical and electromagnetic characteristics of all the objects populating the exposure scenario (including the exposed subject), with the necessary boundary conditions.

As can easily be guessed, the problem becomes enormously complicated, and difficult or impossible to solve, as soon as anything but nearly trivial situations are analysed. In fact, analytical dosimetry at most manages to solve exposure problems in free space, or in the presence of a ground plane simulating the terrain, in which the exposed individual — assumed in an upright position — is modelled by a sufficiently simple geometrical solid (sphere, cylinder, spheroid, ellipsoid) made of homogeneous material. Particular postures or complex environments cannot be modelled, as would instead often be necessary, in particular to analyse exposure problems in workplaces.

Notwithstanding the extreme simplicity of the problems it manages to solve, analytical dosimetry has the merit of providing a mathematical description capable of shedding light on the general physical aspects of the coupling mechanisms between electromagnetic fields and biological organisms.

At low frequencies, where the quasi-static approximation holds, the analytical models allow some characteristics of the interaction to be predicted, among which:

- the internal electric field has an amplitude directly proportional to the intensity of the inducing external field (electric or magnetic), but is in phase quadrature with it;

- the internal electric field is also directly proportional to the frequency;
- the internal electric field induced by an external electric field is inversely proportional to the conductivity of the biological material;
- the internal electric field induced by an external magnetic field is independent of the conductivity of the biological material.

One of the most interesting applications of analytical dosimetry, worth mentioning as an example of the potential of this discipline, was developed by Durney's group. In this application, based on perturbation theory, the electric and magnetic fields are expressed as power series of the free-space propagation constant. After inserting the expressions thus obtained into the field equations and boundary conditions, the coefficients of the corresponding powers are equated term by term. In the quasi-static regime (up to 30 MHz according to the authors), only the first terms of the expansion need to be considered, leading to equations that can be solved analytically without excessive difficulty in spheroidal [9,10] and ellipsoidal [11,12] geometrical models of the human organism.

4. Numerical dosimetry

Numerical dosimetry makes use of computational techniques to pursue the solution of the coupling equations through the use of a digital computer. To this end, the generality of the analytical formulation must be given up, analysing specific, particular problems instead. In return, the ever-increasing processing speed and memory availability of modern computers make it possible to model complex situations and thus tackle problems of a certain realism as well.

The applications of numerical dosimetry follow, in most cases, a series of standard steps, briefly described below.

4.1 Segmentation

Segmentation is the process by which a mathematical model of the exposed organism — for instance a human organism — is built. In practice, the organism is replaced by a set of geometrical solids of sufficiently regular shape, generically called "segments". In the coarsest cases, the segments are spheres or cylinders of macroscopic size, directly modelling body parts such as the head, the trunk, the limbs. In the most refined cases, the organism is subdivided into a large number of small elementary cubes (called voxels) [13]. Obviously, the smaller the voxels, the higher the resolution obtained but, on the other hand, the greater the memory and computing-time requirements needed to complete the assessment. Edge values of the order of a few millimetres, or even less, are in use.

4.2 Dielectric characteristics of tissues

The next step consists in assigning to each segment, considered homogeneous, a pair of values for the so-called dielectric properties, namely the electrical conductivity and the relative dielectric constant (or permittivity), obviously taking into account the frequency at which the investigation is to be carried out.

In the case of microscopic voxels, this goes through the identification of the tissue type each voxel is made of, generally established on the basis of the organ it belongs to. In the case of macroscopic segments, instead, one either tries to identify a prevailing tissue in each segment, or tries to determine values representing a weighted average of the dielectric properties of the various tissues present in it.

In both cases, the respective dielectric properties must be traced back from the tissue types. In this regard, the most comprehensive work to date is the one carried out in the mid-1990s by Camelia Gabriel's group [14,15,16,17], which led to the development of a parametric model capable of representing the dielectric properties of biological tissues in the frequency range from 10 Hz to 100 GHz, and also allowed the values of the 14 parameters of the model to be determined for 45 different human tissues. On-line applications for the use of this model have also been developed at the web sites of the US FCC [18] and of CNR-IFAC [19].

A different approach is the one that allows the 3D conductivity and permittivity map of an organism to be built without going through segmentation and tissue-type identification, but in a more direct and automatic way, for instance from the processing of magnetic resonance imaging (MRI) images. The method, initially developed for the VHF band, is suitable for extension to higher frequencies, but not to lower ones. Segmentation (still necessary for the application of the numerical techniques) is applied afterwards, directly on the 3D map of the dielectric properties.

4.3 Solution methods

At this point it is necessary to derive from Maxwell's equations a set of differential or integral equations well suited to the problem to be studied and to the geometry chosen for the segments. An approach must then be identified that allows these equations to be transformed into a numerically solvable system (for instance, a linear system of algebraic equations), and finally the most efficient solution algorithm must be adopted.

The methods proposed are so numerous and diverse [20,21] that a comparative review cannot be attempted here; we shall therefore limit ourselves to brief mentions. Among the most widespread methods we recall the method of moments [22], the family of finite-difference methods, the finite-element method, and the FDTD (finite-difference time-domain) method [23].

The method of moments is mainly suited to problems using few macroscopic segments, since it requires a memory availability proportional to N^2 and a computing time proportional to N^3 — requirements that become prohibitive with a very large number N of segments, such as the one obtained when using millimetre-sized voxels. On the contrary, the finite-difference methods

(including the FDTD method) have memory and computing-time requirements directly proportional to N. On the other hand, the number of segments N needed by the latter is intrinsically larger than that needed by the method of moments, owing to the need to model, besides the exposed subject, a sizeable region of space around it, so as to satisfy the necessary boundary conditions.

5. Some typical results

Obviously, we can only give here a very brief glance at the wealth of results provided by electromagnetic dosimetry.

5.1 Internal electric field in the quasi-static regime

At the lowest frequencies, where the quasi-static approximation holds, the coupling problems to the electric field and to the magnetic field can be tackled and solved separately.

One finds that the intensity $E_i^{(E)}$ of the internal electric field induced in the tissues by an external electric field is directly proportional to the intensity E_e of the unperturbed external field and to the frequency:

$$E_i^{(E)} = k_E f E_e \qquad \text{(Eq. 3)}$$

The proportionality constant k_E is called the dosimetric coefficient (for the electric field) and depends essentially on the body region and on the conductivity of the tissue involved. Its typical value for the head and chest region is about 1.5×10^{-8} (V/m)/Hz/(V/m) (assuming an average conductivity of 0.2 S/m), while the conservative average value used by the ICNIRP guidelines [1] and by the European regulations [2,3] is 10×10^{-8} (V/m)/Hz/(V/m).

Similarly, the intensity $E_i^{(B)}$ of the internal electric field induced in the tissues by an external magnetic field is directly proportional to the induction flux density B_e and to the frequency:

$$E_i^{(B)} = k_B f B_e \qquad \text{(Eq. 4)}$$

The dosimetric coefficient k_B depends mainly on the body region involved. Its typical value in the chest region is about 0.6 (V/m)/Hz/T, while the average value used by the international standards is 2 (V/m)/Hz/T.

5.2 Average SAR as a function of frequency

The average value of the SAR induced in an organism by an electromagnetic field of given amplitude has, as a function of frequency, a typical resonant behaviour. At low frequencies, the SAR grows with the square of the frequency (since, as seen above, the internal electric field is proportional to the frequency), until it reaches a rather marked peak. The peak occurs at a frequency value that depends on the size of the organism and that, in particular, is higher the shorter the individual's stature. Past the resonance peak, the SAR initially decreases with

frequency and then tends to settle on a constant value. Typical SAR curves as a function of frequency for various statures and field polarisations can be found in the Radiofrequency Radiation Dosimetry Handbook [24].

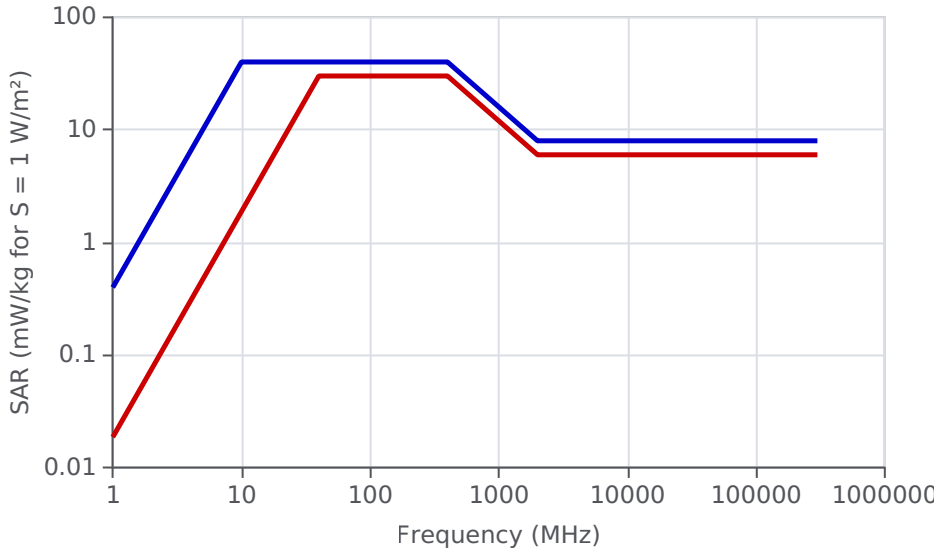

Figure 1. *Behaviour of the average SAR (normalised to 1 W/m²) as a function of frequency. Literature results (lower curve) and conservative value adopted by the standards (upper curve).*

For use by safety standards, an envelope of multiple SAR-versus-frequency curves is considered, corresponding to various statures capable of representing children, women and adult men. The result is shown in Figure 1. The lower curve shows the envelope of the dosimetric results available in the literature, the upper curve represents the set of values conservatively adopted by the standards. In both cases, this is the SAR in mW/kg averaged over the whole organism and referred to a whole-body exposure to an electromagnetic field with an intensity of 1 W/m².

6. Conclusions

Electromagnetic dosimetry is an interesting discipline, both from the standpoint of knowledge and for its important applications in the regulatory and protection field.

Among the various techniques, the most advanced and promising is undoubtedly numerical dosimetry, whereas the experimental and analytical approaches have to face significant limitations.

In-vivo experimental dosimetry is limited to the few measurements that can be performed non-invasively. More satisfactory measurements can be performed on phantoms, but one still has to face both the difficulty of building geometrically realistic models endowed with the necessary physical characteristics, and some technical issues that penalise the accuracy of the measurement process proper. Although some of the problems mentioned may perhaps be

partially overcome by further research, it nevertheless seems unlikely that experimental dosimetry can play a decisive role in future applications, apart from the possibility of being used for the validation of numerical models.

On the other hand, analytical dosimetry is constrained by intrinsic limitations and practical difficulties that make its application to complex problems extremely troublesome. It remains, however, irreplaceable for its ability to give a qualitative insight into the physics of the coupling mechanisms between the electromagnetic field and biological organisms.

Numerical techniques, instead, appear to be undergoing great development, bound to progress hand in hand with the advances of computer technology. We can expect applications to ever more complex problems, with multiple sources and realistically, minutely modelled environments, as is needed, in particular, for applications related to occupational exposure. Much remains to be done to develop accurate, very-high-resolution models of the human organism and, above all, to acquire a better knowledge of the dielectric characteristics of human tissues, particularly at the lowest frequencies.

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