ELECTROMAGNETIC FIELDS DOSIMETRY

Peter Gajšek

Institute of Non-Ionizing Radiation (INIS), Ljubljana, Slovenia

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Abstract: In the last three decades, the use of devices that emit radiofrequency (RF)[1] electromagnetic fields has increased dramatically. The proliferation of RF devices has been accompanied by increased concern about ensuring the safety of their use. Throughout the world many organizations, both government and non-government, have established RF safety standards or guidelines for exposure. Because of different criteria, the former USSR and some of the Eastern European countries have more stringent safety standards than most Western countries. Differences in the exposure limit values in electromagnetic field (EMF) standards between some Eastern European and those of Western countries are over two orders of magnitude. These differences have raised concerns about the lack of uniformity and have led to public concern and distrust about EMF exposures from the increased use of various EMF sources in the living and working environment. Thus, better methods are needed to properly measure, extrapolate or relate effects observed in animals to those expected to be found in people. The resulting data could lead to modification of existing safety standards or setting of new safety standards. Accurate dosimetry represents an essential element of the research in determining the biological effects of electromagnetic fields.

Dozimetrija elektromagnetnih polj

Ključne besede: dozimetrija elektromagnetnih polj, EMF standardi, vplivi EMF na ljudi

Izvleček: V zadnjih treh desetletjih smo priča dramatičnega povečanja rabe naprav, ki oddajajo radiofrekvenčna (RF) elektromagnetna polja (EMF). Povečano rabo RF naprav je spremljala povečana skrb glede zagotavljanja njihove varne rabe. Mnoge vladne, oz. nevladne organizacije po svetu so pripravile varnostne standarde in priporočila za RF obsevanje. Zaradi različnih kriterijev imajo bivše države ZSSR in nekatere vzhodnoevropske države strožje varnostne standarde kot večina zahodnoevropskih držav. Razlike v limitnih ekspozicijskih vrednostih v EMF standardih med zahodnoevropskimi in nekaterimi vzhodnoevropskimi državami so tudi več kot dva reda velikosti. Te razlike so povzročile zaskrbljenost zaradi neusklajenosti standardov in so privedle do javnega dvoma in nezaupanja do izpostavljanja EMF sevanju kot posledica povečane rabe različnih naprav, ki so izvori tega sevanja v delovnem in življenjskem okolju. Zaradi tega potrebujemo boljše metode za ustrezne meritve, ekstrapolacijo in primerjavo vplivov opaženih pri živalih s tistimi, ki jih pričakujemo pri ljudeh. Tako pridobljeni podatki lahko vodijo k spremembi obstoječih varnostnih standardov ali k zasnovi novih. Točna dozimetrija predstavlja ključni element pri raziskavah za določanje bioloških učinkov elektromagnetnih polj.

Introduction

Electromagnetic energy is absorbed non-uniformly in biological tissues (D'Andrea et al. 1977, 1985; Gandhi et al., 1979). Furthermore, a large number of factors such as a body's shape and position as well as its orientation in the field will produce new non-uniform distributions (Durney et al., 1978; Gandhi, 1974). In short, there is no single answer to the question, "How much electromagnetic field (EMF) energy will be absorbed?" Nevertheless, in order to make safe use of EMF emitting devices, a number of techniques for measuring EMF exposure have been devised. Unfortunately, all have limitations. It is understandable then, why the development of mathematical dosimetry modeling techniques and sufficiently powerful computer hardware has resulted in the rapid adoption of dosimetry modeling as a principle tool in determining EMF exposure.

Computer-based dosimetry modeling provides great advantages by returning more information about an exposure than empirical techniques and with considerably less effort. But before this tool transitions into the hands of health safety officers and system designers, it must be verified under a wide variety of conditions using available analytical and empirical dosimetry techniques to verify its accuracy and limitations.

The state of empirical dosimetry has recently been reviewed (Chou et al., 1996) and is described in detail in the Radiofrequency Radiation Dosimetry Handbook (Durney et al., 1986). It is important to briefly review the techniques, as these will be the source of the empirical verification of any EMF dosimetry model.

Empirical Dosimetry

Baseline temperature measurements. Since absorbed EMF energy produces heat, measuring changes in temperature is the principal means of measuring EMF dose.

1 The radiofrequency portion of the electromagnetic spectrum extends over a wide range of frequencies, from about 10 kHz to 300 GHz.

To measure changes, a baseline temperature is required. One method is to allow the sample to equilibrate to the ambient temperature of the exposure chamber. An extended equilibration time is possible with stable samples; however, with biological specimens a long equilibration time is accompanied by changes in permittivity properties. An alternative procedure (Gambrill et al., 1993; Lu et al., 1993), which avoids this problem, is used with unstable samples such as biological tissues. Baseline temperature data is collected for a few minutes before and after the exposure. The average rate of temperature change during the non-exposure periods can be subtracted from the rate of change during exposure. The result is the rate of temperature change produced by the exposure. Using the specific heat for tissue of 0.84, a 1-degree C/minute temperature change is equal to a raw SAR of 58.6 W/kg (Durney et al., 1986). The raw SAR is then divided by the incident field intensity at the site of the measurement to convert to normalized SAR (W/kg/mW/cm^2). In this way, temperature changes due to other factors are isolated from changes due to EMF exposure. This allows the use of thermally unstable samples such as fresh carcasses.

Exposure parameters. In order to maximize sensitivity to temperature changes resulting from EMF exposure and minimize the effects of other factors several considerations must be taken into account when selecting exposure parameters. First, power levels should be selected to produce as rapid a temperature rise as can be accurately detected, in other words, a relatively high incident power. Second, the exposure duration should be as brief as possible. The goal is to minimize the effects of thermal diffusion. Third, the temperature of the sample should be kept within the optimal sensitivity range of the thermometers being used. This may make it necessary to allow the sample to cool between exposures.

Measurement Techniques: Infrared Thermometry. A thermographic camera (We use a Radiance I from Amber Engineering, Goleta, CA) can be use to measure temperatures and ultimately SAR across the visible surface of an object (Mason, 1999). Since the camera is non-invasive it can be used in addition to other measurement techniques. A comparison of rendered three-dimensional SAR data and an infrared image can provide dramatic confirmation of finite-difference time-domain (FDTD) output (See Figure 1). Some samples (e.g., spheres and phantoms) can be constructed so that they can be quickly split after an exposure and scanned to visualize the temperatures over surface of the split. Care must be taken to ensure that the surfaces of the split had good electrical contact during the exposure.

Measurement Techniques: Calorimetry. Whole-body averaged SAR in phantoms and animal carcasses can be determined by twin-well calorimetry (Phillips et al., 1975, Blackman and Black, 1977; Allen and Hunt, 1979; Chou et al., 1984). Two identical samples are brought to temperature equilibrium. One is then exposed. Immediately after exposure, both are placed in the calorimeter wells. The calorimeter measures the heat diffusion for the exposed and unexposed samples, the difference is the amount of EMF energy absorbed by the exposed sample.

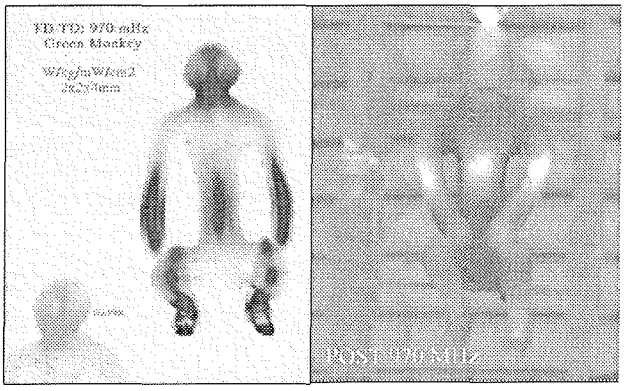

Figure 1. The right panel shows infrared images of a monkey phantom exposed to 970 MHz. Higher temperatures are shown as white. On the left is a rendered image of the results of an FDTD analysis at the same frequency. Very low SARs are transparent, slightly higher SARs are purple, with the highest SARs shown as red. Both images show higher SARs in the arms, torso, ankles and neck. The very white area at the top of the phantom's head (right panel) is an artifact at the opening where the phantom was filled.

Measurement Techniques: Temperature Probes. Non-perturbing temperature probes are inserted into locations of interest. Baseline, exposure, and post-exposure temperatures are collected. Ideally, the temperature at the site of the probes will rise approximately one degree C during the exposure. These data are then analyzed as described above to convert the temperature data to normalized SAR. Results for a phantom monkey at three frequencies are shown in Figure 2. FDTD predictions were used to guide the placement of the temperature probes.

Implantable E-field probes. This type of probe can be inserted into a sample in the same manner as the non-perturbing temperature probes just described. However, these probes measure the intensity of the E-field at the location of the probe. SAR can be directly calculated from the E-field (SAR = s÷E÷^{2}/rm ; where s=conductivity in siemens/meter, ÷E÷ is the electric-field strength in RMS volts/meter and rm is the mass density in kilograms/cubic meter). In addition, these measurements can be performed very quickly and at very low powers, so over heating of target is not an issue. The disadvantage of these probes is their lack of stability. Measurements are sensitive to many factors that would not alter a temperature-based system. As such these measurements must be performed with extreme care. Furthermore, the current generation of probes is quite large relative to the non-perturbing temperature probes; this increases the difficulty of using these probes with biological samples.

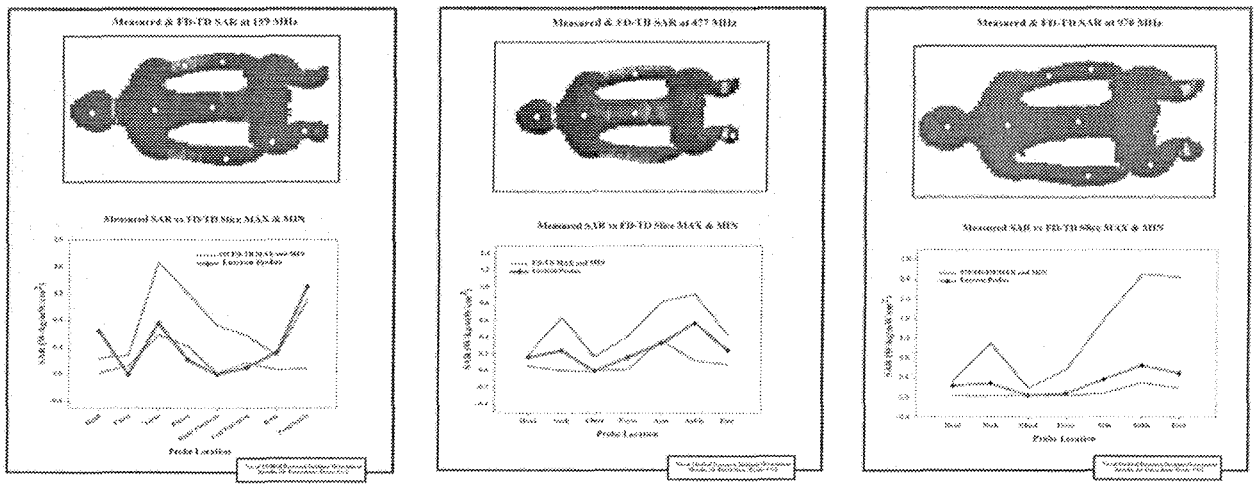

Figure 2. Three panels comparing FDTD results (rendered images and gray lines) to temperature probe data (red lines) at eight locations (yellow dots on images). The gray lines represent the range of SAR values in the area corresponding to the temperature probe location.

Dosimetry Samples

Cadavers. When the questions being address concern only SAR, a cadaver is preferable to a live animal, because a live animal's thermoregulatory system will confound temperature-based SAR measurements. However, the tissue will become dehydrated over time so it is best not to wait too long after euthanization. If local SARs are to be measured, temperature probes will be implanted and temperatures recorded before, during and after exposures.

Spheres. The geometry of a sphere is artificial but very useful. Data collected from a homogeneous or multi-layered sphere are a useful test of the predictions of FDTD. The MIE procedure provides an important mathematically exact reference value for the sphere, which is easily modeled in both FDTD and the laboratory. First derived by Mie (1908), this scattering solution is widely used in EMF and optics. Harrington (1961) gives the exact solution in detail, and programs are available giving the exact near- and far-field results to which we can compare the FDTD results. At NHRC-DET, we use a program developed by Bell et al. (1977). Finally, because the MIE solution provides an exact value, sphere data can be used to measure error in the empirical values as well

Phantoms. Phantoms are constructed of an EMF-transparent fabric sewn into the desired shape and filled with a tissue-equivalent material. A variety of material recipes have been characterized for different simulated organs (muscle, fat, brain and bone) and a range of frequencies (Guy, 1971; and Chou et al., 1984). Using the same mold, it is possible to place temperature probes in the same locations from session to session. Measuring SAR in phantoms is more reproducible, more convenient, and reduces the number of animals required. The whole-body SAR values with the rhesus monkey phantom are a good approximation of results observed with other methods. However, the localized SARs of the homogeneous phantom differ significantly from the structurally complex carcass and live animal. This difference must be taken into account in bioeffects studies.

Computer dosimetry models

The empirical methods described in the previous section have been the primary source of dosimetry data. However, these methods are labor intensive and may not be easily applicable to humans. In efforts to get more dosimetry information investigators have developed a number of techniques such as the use of phantoms. These techniques make the collection of dosimetry data more efficient. However, each also holds some compromises. In the case of the phantom, it is homogeneous and only roughly shaped like the object it models. Other phantoms have been more realistic, but these are also more difficult to construct. It is not surprising that finite-difference models and high-resolution anatomical data sets would be readily adopted.

The method most frequently used in EMF bioeffects dosimetry is the FDTD. As a finite difference algorithm, FDTD has the advantage of being able to analyze a wide variety of geometries. Unlike finite element or method of moments, FDTD can be more efficiently applied to the very large problems such as a segmented version of the Visible Human male. These advantages have led to the phenomenal growth in the application and development.

FDTD. The FDTD method was originated by Yee (1966) and later developed further by Taflove and colleagues (1975, 1990); Holland (1977), and Kunz and Lee (1978). As more powerful computers became more widely available, use of the FDTD method has increased exponentially

(Shlager, K.L. and Schneider, 1995 and http://www.fdtd.org). Its use in bioelectromagnetics has increased as well by Gandhi and others (Gandhi, 1994; Stuchly and Gandhi, 2000; Dimbylow, 1997). In addition, FDTD is widely used by makers of cell phones to calculate head exposures during cell phone use.

The FDTD method is not limited to bioeffects research it has been extensively used to model antenna, waveguides, and military hardware. Unlike its main competitors, the method of moments (MOM) (Harrington, 1968) and finite element method (FEM) (MacNeal, 1991), the FDTD method is scalable, i.e., the CPU time behaves linear in the problem size N. The MOM and FEM methods require matrix inversions (albeit sparse matrices in FEM) and thus scale as N^3. The MOM method is primarily useful for problems with conducting surfaces, but difficult to apply to permittivity problems of interest here. Its practical limitation is to systems less than 10^6 cells. The FEM method, with its irregular cell structure, is difficult to parallelize efficiently. The FDTD method with its rectangular cell structure is easy to parallelize, and, in the case of the problem at hand, is compatible with the cellular data formats of the monkey and human anatomical models. The main disadvantages of FDTD are object resolution and absorbing boundary conditions (also in FEM), but sophisticated versions of the FDTD method have been developed to handle these problems (Taflove, 1995). On the whole, we judge the FDTD approach to be the best to model the complex biological systems of interest.

Figure 3. Rendering of SAR results at 918MHz using FDTD and 3mm man model.

FDTD Code. The FDTD program used at Brooks AFB is based on code originally developed by Kunz and Luebbers (1993). It has been used to predict whole-body SAR and SAR distributions in spheres, monkey phantom, rhesus monkey, and human models. These models were developed jointly by NHRC-DET and AFRL/HEDR. This FDTD program has been extensively used in the last few years to predict SAR in various models as part of ongoing bioeffects research. Continued development of the code by Luebbers and others has resulted in a commercial product XFDTD (www.remcom.com).

We have made a number of modifications to the original code. We added more materials types to include all of Camellia Gabriel's types and some non-biological materials. The permittivity properties of each of the tissue types are set according to data and fits published by Gabriel (1996). Sample output for 918 MHz with the 3-mm version of the man model is show in Figure 3. The modified code reads the anatomical model files and outputs a 3-D normalized SAR file; mean, minimum, and maximum SARs for each tissue type; and each Z-plane slice. Finally, there is an extensive log file and all file names reflect run parameters. The code has been parallelized using the message-passing interface (MPI) library, which allows for larger and more complex data sets to be modeled. The advantage of using the MPI is that the code can run on parallel computer systems composed of networks of computers. These may be networked workstations, or massively parallel systems such as Linux-based Beowulf systems. These systems are easily constructed of inexpensive PC-hardware.

The Visible Human Project: Male Data Set

The human model is based on the photographic data from Visible Human Project created by the National Library of Medicine (www.nlm.nih.gov/research/visible/visible_human.html) and the University of Colorado Health Science Center (www.uchsc.edu/sm/chs/). A computer-segmented set of the photographic images was created by National University of Singapore and Johns Hopkins University. We limited the number of tissue types based on their size in the body and availability of permittivity properties. Each of the 1878 slices in the XY plane was coded by hand using Adobe Photoshop ™ and a palette of colors that represented the 40 tissue types (See Mason et al, 1995, 1999 for a complete description). It is the largest of the anatomical data sets we have created at 374 million voxels (1878 by 340 by 586). Each voxel is a cube 1 mm on a side. There are two improvements planned to enhance the usability of this data. First, the eyes will be opened. And second, the feet will be rotated and flattened slightly on the bottom to allow the model to make good contact with a ground plain or simulated shoe material. Modeling EMF exposures with this model will require approximately 18 GB of computer memory for FDTD. Smaller versions of this data set with resolutions of 2, 3, 5, 10 and 22 mm have been created and are suitable for some applications. These require considerably less memory but this savings comes at a cost. As the voxel size increases small organs may be distorted or lost, some symmetries may be affect-

ed, organs will change mass slightly and the continuity of elongated structures may be disrupted. These reduced resolution models are created automatically. The process would be as follows for creating a 3-mm anatomical model from a 1-mm model. Layers of air are added to one or more sides of the model volume to make the size of the model an even multiple of the 3 mm. The reduction would then take a cube of 3 by 3 by 3 one-millimeter voxels and based on the most common type in that cube create the single three-millimeter voxel. This process would be repeated for each 3 by 3 by 3 set of 1-mm voxels.

International INITIATIVE - GLOBAL EMF Dosimetry Project

One of the most useful documents in bioelectromagnetics is the Air Force Radiofrequency Radiation Dosimetry Handbook. Now in its 4th edition (Durney et al., 1986), the handbook describes, the principles and techniques for establishing RFR dose. It is a standard in radio frequency dosimetry. The International EMF Dosimetry Project was envisioned as the means of producing the next version of the dosimetry handbook.

The International EMF Dosimetry Project (www.emfdosimetry.org) was established as an international resource that provides state-of-the-science knowledge on EMF dosimetry. This project originated during the North Atlantic Treaty Organization (NATO) Advanced Research Workshop on ***Radio Frequency Radiation Dosimetry and Its Relationship to the Biological Effects of Electromagnetic Fields*** held at Gozd Martuljek, Slovenia, October, 1998.

The overall project goals of the International EMF Dosimetry Project are to promote the field of EMF dosimetry by creating internationally-accepted EMF Dosimetry Handbook and software that describe how EMF dosimetry measurements and calculations should be performed. By employing an open international forum, the Internet, the project should proceed rapidly, at low cost, and the results should be accepted internationally. This project could serve as the common ground for harmonizing EMF exposure standards that are currently unique to most countries.

Potential results of this project include: facilitation of international EMF research efforts and collaborations; assistance in EMF dosimetry predictions and measurements; development of an international research community that will identify EMF dosimetry research areas where further data are required; and rapid and easily accessible communication amongst researchers to avoid duplication of research efforts and maximize research dollars. These results should permit more timely responses to the dosimetry requirements of the EMF community.

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Peter Gajšek
Institute of Non-Ionizing Radiation (INIS),
1000 Ljubljana, Slovenia
Peter.Gajsek@inis.si

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