Use of the Impedance Method for ICNIRP - Related ComplianceTesting of Electronic Article Surveillance Devices

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I. Introduction

Electronic Article Surveillance (EAS) Systems based on the use of alternating magnetic fields at frequencies up to 10-20 MHz are being rapidly introduced into society to prevent unauthorized removal of items from stores, libraries, and hospitals. The EAS systems may take the form of one or two-sided panels of current-carrying loops or pillars at or near the exit door, and loops hidden in the ceiling and/or the mat on the floor. Another manifestation is the magnetic tag deactivation systems that are mounted as checkout counter top devices. The net result is that an individual passing through or standing close to these devices is exposed to nonuniform vector magnetic fields emanating from these EAS systems.

Limits of induced current densities in the human body have been prescribed in the IEEE [1] and ICNIRP [2, 3] standards that may not be exceeded for exposure of the general public or for occupational situations. Computational methods using heterogeneous anatomically-based models of the human body are acceptable to show compliance of new EAS devices. For the present paper, we have used the widely accepted 3-D impedance method [4-7] to calculate the currents induced in the human body for some representative EAS devices. Since the purpose of the paper is to illustrate the approach and the kind of results that one may expect, the geometrical configurations, the ampere turns and the frequencies have been altered from those used in commercial devices.

II. The Impedance Method

As described in [7], the impedance method has been used for a number of bioelectromagnetic problems including operator exposure to spatially variable magnetic fields of induction heaters [5], linear or circularly polarized RF magnetic fields of magnetic resonance imagers [6] etc. The anatomically-based model of the human body obtained from the MRI scans of a male volunteer has voxel dimensions of 2×2 mm along x- and y-axes (side to side and front to back, respectively) and a thickness of 3 mm along the vertical (z) axis. As described in [9], this model has been classified into 31 tissue types. The tissue types are fat, muscle, bone, compact bone, cartilage, skin, brain, nerve, cerebrospinal fluid (CSF), pineal gland, intestine, spleen, pancreas, heart, blood, eye, eye humor, eye sclera, eye lens, ear, liver, kidney, lung, bladder, stomach, ligament, spinal cord, testicle, spermatic cord, prostate gland, and erectile tissue.

For low frequencies, where the dimensions of the biological body are small compared to the wavelength, the impedance method has been found to be highly efficient as a numerical procedure for calculations of internal current densities and induced electric fields [4-6]. In this method, the biological body or the exposed part thereof is represented by a three-dimensional (3D) network of impedances

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(resistances in our case) whose individual values are obtained from the complex conductivities $\sigma + j\omega\varepsilon$ for the various locations of the body. The impedances for various directions for the three-dimensional network can be written as

$$Z_m^{i,j,k} = \frac{\delta_m}{\delta_n \delta_p \left(\sigma_m^{i,j,k} + j\omega\varepsilon_m^{i,j,k}\right)}$$

where i, j, k indicate the cell index; m is the direction, which can be x, y, or z, for which the impedance is calculated; $\sigma_m^{i,j,k}$ and $\varepsilon_m^{i,j,k}$ are the conductivities and the electrical permittivities for the cell i, j, k; δ_m is the thickness of the cell in the mth direction; and δ_n and δ_p are the widths of the cell in directions at right angles to the mth direction.

For comparison with the safety guidelines proposed by ICNIRP [2, 3], it is necessary to focus on the induced current densities for the central nervous system (CNS) tissues e.g. the brain and the spinal cord. It is recognized that the finer resolution ($2 \times 2 \times 3$ mm) model though available for the whole body is very cumbersome to use because of the very large number of voxels in excess of 10 million. We have, therefore, used a two-step process to calculate induced current densities for the small volume CNS tissues such as the spinal cord.

For step 1, a finer resolution of $2 \times 2 \times 3$ mm for each of the voxels is not necessary for the human body model. We have, therefore, combined $3 \times 3 \times 2$ cells along x-, y-, and z-directions, respectively to obtain new cells of dimensions $6 \times 6 \times 6$ mm along each of three axes. Using the tissue properties given in a number of references [see e.g. 8, 9], we have obtained the conductivities to use for each of the tissues in the model at a selected exposure frequency of 30 kHz. It should be mentioned that contribution to induced currents and electric fields due to displacement current densities ($j\omega\varepsilon E$) is negligible as compared to conduction current densities (σE). It is, therefore, customary to include just the conductivities and neglect $\omega\varepsilon$ by comparison for dosimetry at quasi-static frequencies such as 30 kHz used here. Since the conductivity for muscle and the spinal cord is anisotropic and each of the coarser cells of the new (nominal) 6 mm resolution model consists of $3 \times 3 \times 2$ cells of the original MRI-based model, directionally-averaged conductivities are calculated for each of the voxels and used for all calculations in step 1 of the calculations.

For step 2, we identify the regions of the body containing the spinal cord and use the original tissue classifications with resolutions of $2 \times 2 \times 3$ mm for these regions. The region surrounding the spinal cord thus identified has dimensions of $6 \times 12 \times 66$ cm ($30 \times 60 \times 220$ cells) along x-, y-, and z- directions, respectively. A new impedance model is then derived for this subvolume from the tissue classifications with resolution of $2 \times 2 \times 3$ mm in the original human body model. The currents calculated as a result of step 1 are used as input at the various nodes for this higher resolution model.

III. Numerical Results

Here we give an example of a one-sided EAS system consisting of two rectangular coils each of width 50 cm and height 60 cm with an overlap of 10 cm carrying in-phase currents of 100 A turns rms for each of the coils. This system is sketched in Fig. 1. Using Biot-Savart's law of electromagnetics, we have written a computer program to calculate the magnetic fields B_x, B_y, B_z for each of the locations close to the pair of coils. A symmetrically-placed model of the human body is assumed to face the y direction to the right of the coils at a distance of 30 cm from the outside of the arm to the plane. From the incident magnetic fields, we can calculate the induced current densities J_x, J_y, and J_z and hence the total current density $J = (J_x^2 + J_y^2 + J_z^2)^{1/2}$ for each of the voxels of the human body model, respectively. According to the ICNIRP guidelines [2, 3], the basic restriction for exposure to EM fields at 30 kHz is a current density of 60 mA/m^2 averaged over a cross section of 1 cm^2 perpendicular to the direction of the current. We have, therefore, modified our impedance method code to obtain the current densities averaged over any 1 cm^2 of the model. Given in Table 1 are the calculated volume average current densities and the maximum 1 cm^2 area-averaged current densities for the various organs. For comparison with the ICNIRP safety guidelines [2, 3], it is necessary to focus on the induced current densities for the central nervous system tissues i.e. the brain and the spinal cord. As seen from Table 1, the maximum 1 cm^2 area-averaged current density for the brain is 6.3 mA/m^2. Also the maximum 1 cm^2 area-average current density for the spinal cord is 32.3 mA/m^2. Both of these values are less than 30 mA/m^2 prescribed in the ICNIRP safety guidelines [2, 3].

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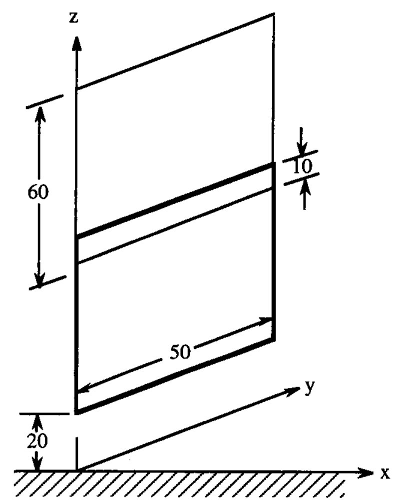

Fig. 1. An assumed EAS system using a pair of rectangular coils with an overlap of 10 cm. The lower rung of the bottom coil is assumed to be 20 cm off the ground plane. The marked dimensions are in cm.

Table 1. The calculated organ-averaged (J_{av}) and maximum 1 cm^2 area-averaged current densities for the EAS system.

Organ	$J_{av}(mA/m^2)$	$J_{max}(mA/m^2)$
Brain	3.3	6.3
Heart	24.5	47.1
Liver	17.8	32.0
Kidneys	24.9	51.5
Bladder	25.1	52.6
Pancreas	7.3	9.3
Intestine	51.3	91.6
Spleen	8.1	15.9
Stomach	26.4	77.2
Testicle	27.6	33.6
Prostate	6.3	8.9
Lungs	7.8	19.5