Non-Uniform Magnetic Field Exposure Assessment Using Coupling Factors Based on 3-D Anatomical Human Model

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Coupling factors are calculated in order to facilitate non-uniform magnetic field exposure assessment. Coupling factor takes into account the characteristics of the localized non-uniform field source, whereas reference levels in EMF (electromagnetic field) safety guidelines only consider uniform field exposure. The calculations are performed using several different equivalent human models including simplified homogeneous models and complex anatomical model. Two types of non-uniform sources are considered; a circular coil in a vertical plane and straight wire in a horizontal plane. For modeling and quasi-static electromagnetic simulation of the complex anatomical human model, Sim4Life software was used, which applies finite element method to graded voxel meshes. The dependence of coupling factor values on the various parameters including source type, the distance between source and human model, coil radius, and type of the equivalent human model used is analyzed.

***Index Terms*—Bioelectric phenomena, coupling factor, dosimetry, induced current density.**

I. Introduction

With proliferation of home appliances and electronic devices utilizing electromagnetic field (EMF) such as induction cookers and wireless chargers, it is becoming increasingly important to protect general public and workers from possible adverse health effects of EMF. EMF safety guidelines such as ICNIRP 2010 guideline and IEEE C95.1-2005 standard define exposure limits in terms of induced current density or electric field in human body based on established health effects. Since induced electric field is difficult to measure, reference levels are provided in terms of electric or magnetic field strength in free space for practical exposure assessment purposes. However, these reference levels are derived assuming uniform field exposure, and often lead to overestimation of induced electric field when human body is exposed to a localized non-uniform field source. In order to overcome this problem, coupling factor *K* was defined and introduced in IEC standards. Coupling factor *K* takes into account the characteristics of the non-uniform field sources and simplifies EMF exposure assessment procedures [1].

In order to use coupling factor *K* in EMF exposure assessment, its value must be pre-computed using numerical and/or analytic methods. The value of *K* depends on various parameters of the calculation including the type of the equivalent human model used. In the IEC 62226-2-1 standard, *K* values were calculated using a homogeneous 2-D disc as an equivalent human model [1]. Recently, Shim et al. have calculated coupling factors for non-uniform, low-frequency magnetic field exposure situations [2] using 3-D human models. However, in the previous work, either prolate spheroid or simplified human model with homogeneous conductivity was used as an equivalent human model. In this paper, coupling factors are calculated for various magnetic field exposure conditions using a 3-D anatomical human model with inhomogeneous tissue compositions in order to improve the accuracy. Also, separate definitions of coupling factors given in different IEC standards will be analyzed and their practical usage will be discussed in the full paper.

II. Coupling Factor *K* and Magnetic Field Exposure Conditions

In the IEC 62226-2-1 standard, coupling factor *K* is defined as follows [1]:

$$K = J_{nonuniform} / J_{uniform} \quad (1)$$

where $J_{nonuniform}$ is the maximum induced current density in the human model exposed to the non-uniform magnetic field from a localized source, and $J_{uniform}$ is the maximum induced current density in the human model exposed to the uniform magnetic field. Assuming that strength of the non-uniform magnetic field is the same as the uniform field at the model surface location closest to the source, the current density induced by a non-uniform field ($J_{nonuniform}$) is always lower than that by a uniform field ($J_{uniform}$). Hence, the coupling factor *K* quantifies the reduction of induced current for non-uniform field, and the range of *K* is given as $0 < K < 1$.

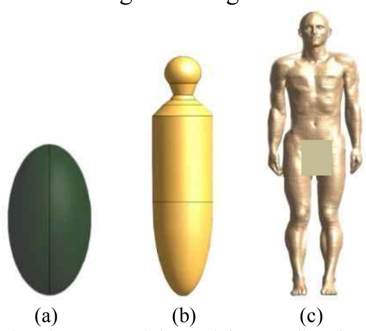


Fig. 1. 3-D equivalent human models used for coupling factor *K* calculation. (a) Prolate spheroid. (b) Simplified human model from IEC 62311 standard. (c) Anatomical human model based on MRI images (Duke).

Three different 3-D equivalent human models are used for coupling factor calculation; a prolate spheroid, a simplified human model from IEC 62311 standard [3], and an anatomic human model based on MRI images (Fig. 1). The height and width of the prolate spheroid is 0.8 m and 0.4 m. Simplified human model from IEC 62311 standard is composed of head and torso, and the height of the model is 152.8 cm. The electrical conductivity is set as σ = 0.2 S/m for both models. For an anatomical human model, “Duke” model of the Virtual Family was used, which was built from medical image data obtained by MRI [4], [5]. The model is composed of 74 body tissues which have different values of electrical conductivity, and the height of the model is 170 cm.

Two types of non-uniform magnetic field sources are investigated in this paper, a straight wire in a horizontal plane and a circular coil in a vertical plane (Fig. 2). The frequency of the current source is set as 50 Hz. Induced current density in the human model and coupling factor K are calculated as the distance d between the human model and the source is varied ($10 \le d \le 300$ mm). For the radius r of the vertical coil, two cases are considered (r = 20 and 160 mm).

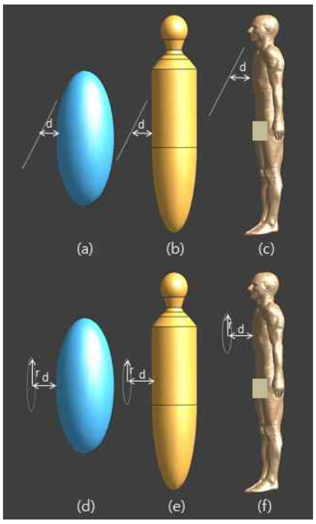


Fig. 2. Magnetic field exposure conditions for different 3-D human models.

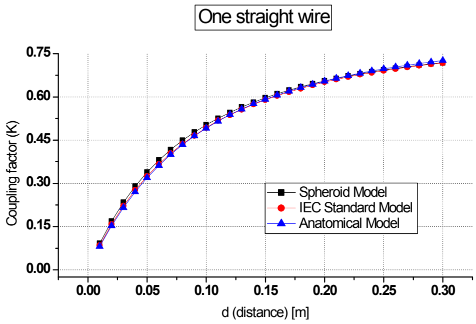
III. CALCULATION AND ANALYSIS OF COUPLING FACTOR K

Quasi-static electromagnetic solver of Sim4Life software was used for coupling factor calculation [6], which can deal with an anatomical human model (Duke). In the solver, the finite element method is applied to graded voxel meshes to enable the analysis of complex anatomical human models. The vector basis function $\tilde{\boldsymbol{N}}_1^e$ for edge number 1, for example, of the rectangular brick element can be written as [7]:

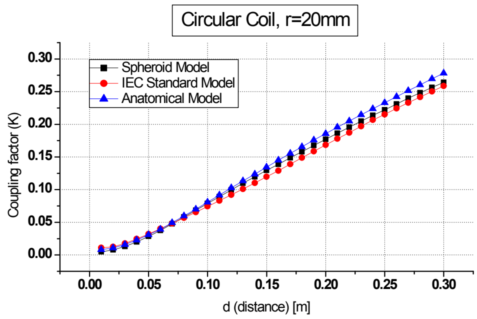
$$\tilde{\boldsymbol{N}}_1^e = \frac{1}{h_y h_z}(y_c^e + \frac{h_y}{2} - y)(z_c^e + \frac{h_z}{2} - z)\boldsymbol{a}_x \quad (2)$$

where (x_c^e, y_c^e, z_c^e) is the center point of the element, and h_x, h_y and h_z are element side lengths.

Maximum current density in the human model will depend upon the voxel resolution, and it is also susceptible to boundary error when there is a large contrast in conductivity between voxels. Thus, 99th percentile values of induced current density are used for calculation of $J_{uniform}$ and $J_{nonuniform}$ instead of maximum values [8]. The calculated K values are plotted in Fig. 3, and it can be seen that there are considerable discrepancies between K values of homogeneous human models and those of an anatomical model.



(a)



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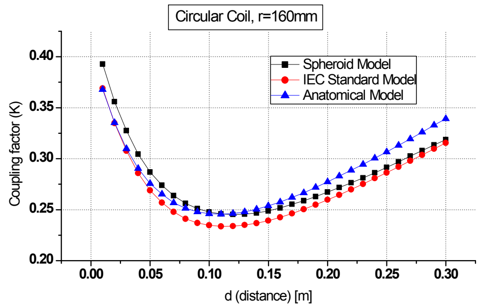

(c)

Fig. 3. Plots of coupling factor K. (a) Straight wire. (b) Vertical circular coil (r=20mm). (c) Vertical circular coil (r=160mm).

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