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On the use of the boundary element analysis in bioelectromagnetics

Dragan Poljak [a,*], Damir Cavka [a], Hrvoje Dodig [b], Cristina Peratta [b], Andres Peratta [b]

[a] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Ruđera Boškovića 32, 21000 Split, Croatia
[b] Wessex Institute of Technology, Ashurst, Southampton SO40 7AA, United Kingdom

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ABSTRACT

The paper reviews a boundary element analysis of the human exposure to electrostatic, low frequency (LF) and high frequency (HF) electromagnetic fields. The formulation for the low frequency exposures is based on the quasi-static approximation and the related Laplace equation form of the continuity equation. The assessment of high frequency exposures is based on the Helmholtz equation. The solution of the governing equations is carried out using certain boundary element procedures. Some illustrated computational examples are related to the human head exposed to electrostatic field from video display units (VDUs), pregnant woman/foetus exposure to extremely low frequency (ELF) fields from power lines and the human eye exposed to high frequency (HF) electromagnetic radiation.

Contents

1. Introduction

The enormous growth of modern power and communication systems in modern society has increased the public concern regarding possible health risk due to exposure to electromagnetic fields generated by these systems.

A comprehensive view to the subject could be found in many review papers, e.g. [1,2]. On the other hand, human being is a rather complex structure to analyze as measurement of induced currents and fields in the body in a realistic scenario is not possible. Consequently, regarding measurements of relevant electromagnetic quantities, the phantoms having some electrical parameters corresponding to humans are often used [3–5], while the theoretical dosimetry procedures for the human exposure assessment are related to the use of sophisticated numerical methods [6–8].

* Corresponding author. Tel.: +385 914305698; fax: +385 21305776.
E-mail address: dpoljak@fesb.hr (D. Poljak).

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Generally, the numerical models used in bioelectromagnetics can be divided into two groups:

- The realistic models of the human body (or specific organs) with a high discretization density – mostly based on Magnetic Resonance Imaging (MRI) [1,9–14]. These models require rather high computational cost.
- Simplified models, computationally much less expensive [1–5,15] – fail to ensure accurate results in most of the scenarios.

This paper reviews the use of boundary element procedures in bioelectromagnetics by the authors. The low frequency (LF) and high frequency (HF) exposures are considered.

Illustrated computational examples presented throughout this work are related to human head exposed to electrostatic field from video display unit (VDU), pregnant woman/foetus exposed to high voltage (HV) extremely low frequency (ELF) electric fields generated by overhead power lines [16,17] and to the human eye exposed to plane wave [13,18]. The electrostatic and LF analysis is based on the calculation of induced currents and electric fields obtained by solving the corresponding Laplace equation type via BEM [16,17], while the HF exposure analysis is based on the assessment of SAR distribution and the corresponding BEM solution of vector Helmholtz equation [18].

In particular, it is worth noting that BEM represents one of the promising approaches for static and ELF dosimetry. As documented in ICNIRP [20,21] the stair-casing error is significant not only for the current density, but also for the internal electric field, i.e. 99th percentile value of *E*-field is suggested. However, such a measure is not quite appropriate for localized exposures. Therefore, BEM oriented approach seems rather important aiming to verify conventional Finite Difference (FD) based approaches.

2. Theoretical dosimetry basics

Depending on the frequency, the electromagnetic radiation is classified as non-ionizing or ionizing. Non-ionizing fields are split into two main categories: low frequencies (up to about 30 kHz) and high frequencies (from 30 kHz to 300 GHz).

While LF fields may cause excitation of sensory, nerve and muscle cells, HF fields, due to the resonance effect (the body dimensions become comparable to the external field wavelength), are absorbed by the body, and the related heating effects are dominant.

In the case of LF exposures the thermal effects are negligible, and possible nonthermal effects are related to the cellular level.

Note, that according to ICNIRP 1998 guidelines [20] the current density was a principal parameter for the estimation of LF exposure effects, while the 2010 ICNIRP guidelines [21] propose the induced electric field instead of the induced current density. However, there is a substantial amount of the numerical results for the current density in the relevant literature, therefore, for the comparison purpose this review paper pertains to the assessment of current density, as well.

On the other hand, the main goal in HF dosimetry is related to thermal effects, i.e. to assess the level and distribution of the electromagnetic energy absorbed by the body. The main dosimetric quantity for HF fields is the specific absorption rate (SAR).

Theoretical models are necessary to simulate various exposure scenarios, and thereby establish safety guidelines and exposure limits for humans [21]. Due to the mathematical complexity of the problem most of the early stage researchers investigated simple models such as plane slab, cylinders, homogeneous and layered spheres and prolate spheroids [22].

As a matter of fact, sophisticated numerical modeling is required for a successful prediction of the internal field distribution in realistic body models [16,17]. Recent anatomically based computational models comprising of cubical cells are mostly related to the application of the Finite Difference Time Domain (FDTD) methods. The Finite Element Method (FEM) and Boundary Element Method (BEM) are generally used to a somewhat lesser extent [22, 25].

2.1. Exposure to low frequency fields

The current density inside the human body can be induced due to an external electric or magnetic field. Internal current density J due to electric fields is axial in nature and is given by the constitutive equation:

$$J = \sigma E \tag{1}$$

where σ is tissue conductivity while E is the corresponding internal electrical field.

The internal current density generated by the magnetic field forms loop and is defined by expression [22]:

$$J = \sigma \pi r f B \tag{2}$$

where B is the corresponding magnetic induction normal to the human body, f is the operating frequency and r is the radius of the loop.

2.2. Exposure to high frequency fields

The basic quantity in HF dosimetry is the specific absorption rate (SAR) defined as the rate of energy W absorbed by, or dissipated in the unit body mass:

$$SAR = \frac{dP}{dm} = \frac{d}{dm}\frac{dW}{dt} = C\frac{dT}{dt} \tag{3}$$

where C is the specific heat capacity of tissue, T is the temperature and t denotes time.

Also, SAR is proportional to the square of the internal electric field:

$$SAR = \frac{dP}{dm} = \frac{dP}{\rho dV} = \frac{\sigma}{2\rho}|E|^2 = \frac{\sigma}{\rho}|E_{rms}|^2 \tag{4}$$

where E and E_{rms} is the peak and root-mean-square value of the electric field, respectively, ρ is the tissue density and σ is the tissue conductivity.

The distribution of SAR inside the body generally depends on the incident field parameters, the characteristics of the exposed body, ground effects and reflector effects. The whole body SAR reaches maximal values when the electric field is oriented parallel to the long body axis the whole body SAR reaches maximal values.

3. Exposure to VDU electrostatic field

Video display units (VDU's) based on cathode ray tube (CRT) are sources of many types of radiation e.g. X ray radiation, ultraviolet radiation, infrared radiation, electromagnetic radiation, etc. Recent increasing use of VDUs has caused some concerns of possible adverse effects of these fields to the human health. Thus, it has been proven that the radiation levels, such as levels of X ray radiation, optical radiation, high (~MHz) and low (~kHz) frequency electromagnetic fields stay well below exposure limits [24,25].

However, electrostatic fields and low frequency fields might be associated with some skin diseases, suppression of melatonin, or induction of phosphenes in the eyes, despite of the fact that there