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Stochastic sensitivity of the electromagnetic distributions inside a human eye modeled with a 3D hybrid BEM/FEM edge element method

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ABSTRACT

This contribution was dedicated to the assessment of the electromagnetic (EM) distributions inside a 3D modeled human eye. Since the use of accurate and efficient electromagnetic tools is crucial to obtain such results, an original hybrid boundary element method (BEM)/finite element method (FEM) is presented through the example of an EM wave impinging on the eye corneal region. Due to the variability inherent to the characterizing of living parameters (regarding our frequency range of interest about a few GHz), an accurate modeling of those mostly electrical data is necessary. A simple formalism based upon a "philosophy" close to Monte Carlo requirements is proposed in this paper in order to integrate efficiently and precisely uncertainties in the proposed results. The analysis of the sensitivity of different electrical parameters aims to increase a better knowledge of the EM fields distribution inside an eye. Obviously, both the deterministic EM modeling and the stochastic theoretical basis will be presented. The whole model will be illustrated on numerical examples including different random variables.

1. Introduction and motivations

The human eye is the sensory organ, that converts electromagnetic impulses within visible range into nerve impulses suitable for processing by human brain. Considering the huge variability clearly involved with living material works, the aim of this study is to assess the influence of uncertainties surrounding the electromagnetic properties (relative permittivity and conductivity for Radio Frequency, RF, range around few GHz) of a modeled human eye. Among the diversity of approaches available, this work will require accurate and competitive deterministic methods and stochastic techniques.

One of the most spread statistical techniques to handle with stochastic works remains the well-known Monte Carlo (MC) approach. The MC simulation techniques were introduced in the 1940s to deal with problems that include stochastic parameters from a system with probabilistic features. Its computation is straightforward and implies a mapping between model controlled and response variables using numerical integration and it needs few requirements on the chosen random output [2]. In an integration approach, this technique is well suited for singular (irregular) kernels and it is not compulsory to access analytic information on their statistical form. The "classical" MC reveals independent of the problem dimension and can be used for many stochastic issues involving a high number of random variables (RVs). However, its main disadvantage [3] relies on a slow convergence rate. Thus, it may appear computationally prohibitive and a difficulty may remain to set the threshold defining the MC convergence level.

Various stochastic approaches have been computed with success since 2002 to offer a more realistic view of EM simulations including uncertainties. For instance, one may put the focus on the Unscented Transform (UT) [4–6] or the "Lagrange" Stochastic Collocation (SC) [7–11] methods, the kriging technique [12,13,15], the Polynomial Chaos (PC) expansion [1,16,17], and the Experimental Design (ED) [18,19]. Far from appearing as an exhaustive review of stochastic and statistical methods in electromagnetism, the previous quoted techniques were mainly applied to numerical simulations including various EM domains: shielding effectiveness [4–6,10], scattering and propagation [7,10,19], susceptibility [10–12,18] and/or

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EM Compatibility/Interferences (EMC/EMI) [8,9,16,17] problems. Even if very few works were achieved considering bio-EMC study until [14], the development of this topic has hugely increased [1,15,20–23] in past years.

In this paper, the aim is to present an original and precise deterministic method to model the electric and Specific Absorption Rate (SAR) distributions inside a human eye jointly with an efficient and accurate stochastic method (SC) in order to integrate uncertainties surrounding parameters knowledge. That is the reason why the two following parts will be dedicated to the principles from the deterministic technique and the theoretical stochastic foundations. In the final section, a synthetic view of the numerical results obtained is presented.

2. Deterministic model

Accurately modeling the geometry of an eye has proven to be the significant technical challenge.

2.1. Schematic eye and electrical properties of an eye

In order to accurately calculate electrical field and SAR in the human eye induced by frontal plane wave of power density 10 W/m^2 an accurate view of the eye is required. For the purpose of numerical calculations of electric field inside an eye, we propose a simplified model (27 mm eye model shown in Fig. 1) comparatively to detail anatomy of the human eye that one may find in [28]. The relative dimensions and the relative locations of various eye parts are compiled from references [27–29]. Relying on a cartesian coordinate system given in Fig. 2, the shape of cornea was computed according to the biconical surface equation given by Navarro [30]:

$$x_{cor}(y,z) = \frac{c_y y^2 + c_z z^2}{1+\sqrt{1-(1+Q_y)c_y^2 y^2 - (1+Q_z^2)c_z^2 z^2}} \quad (1)$$

where x_{cor} is the distance along optical axis, Q_y and Q_z are the conic constants, and coefficients c_y and c_z are related to the orthogonal curvatures R_y and R_z respectively as

$$c_y = \frac{1}{R_y} \quad (2)$$

$$c_z = \frac{1}{R_z} \quad (3)$$

In order to simplify the eye model we have chosen orthogonal curvatures to be equal, i.e. $R=R_y=R_z$. Consequently we have $c=c_y=c_z=1/R$ and $Q=Q_y=Q_z$. Thus, Eq. (1) simplifies to

$$x_{cor}(y,z) = \frac{c(y^2+z^2)}{1+\sqrt{1-c^2(1+Q)(y^2+z^2)}} \quad (4)$$

To compute the shape of anterior corneal surface we have used the mean radius of anterior corneal curvature R=7.83 mm and conic constant $Q=-0.18$. For computation of interior corneal surface we have used the mean radius of interior corneal curvature R=6.5 mm and conic constant $Q=-0.66$ as shown in Fig. 2(a).

The shape of the lens and the changing refraction index inside the lens (GRIN) were modeled according to the work of Diaz et al. [31] where GRIN change with the age is modeled with single continuous function:

$$\eta(x,y,z) = 1.371 + \eta_1[\cos(\eta_2 x) - 1] + \eta_3 \sin(\eta_4 x) + \eta_5(y^2+z^2) \quad (5)$$

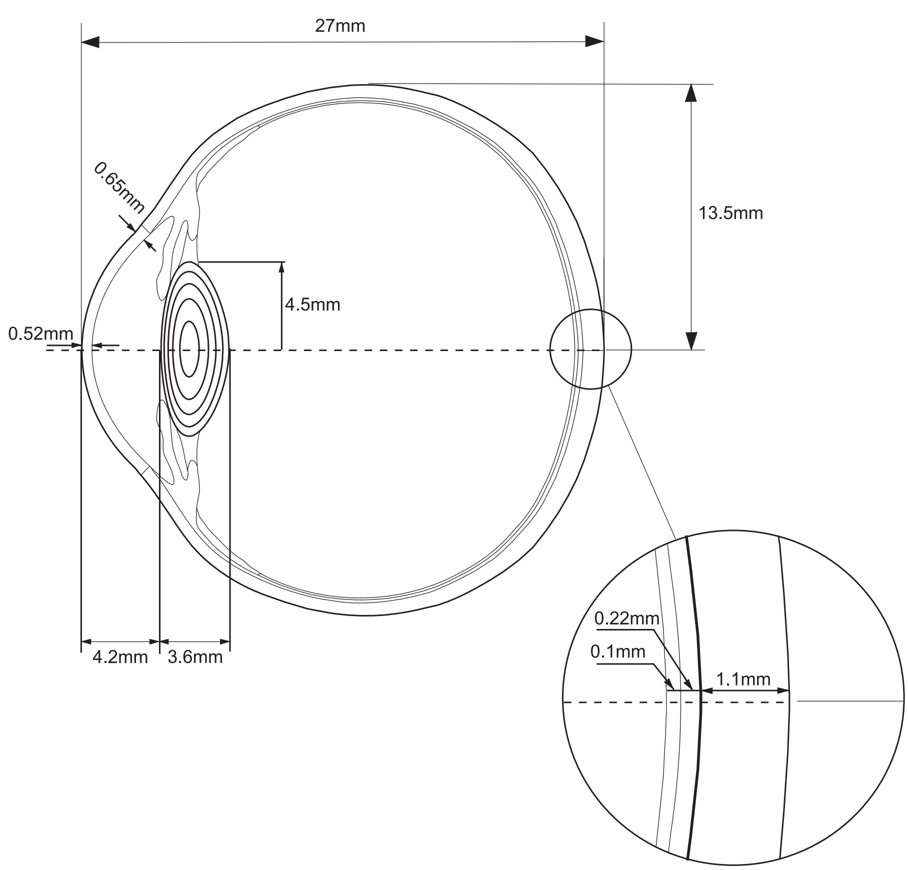

Fig. 1. Cross section of simplified 27 mm schematic eye. Modeled eye parts are cornea, anterior chamber, 5-layer lens, vitreous body, ligaments, ciliary body, sclera and retina.