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# Uncertainty of numerical simulations in bioelectromagnetic problems

***Abstract.*** *The numerical modelling of bioelectromagnetic problems are subject of many issues which could deteriorate its reliability. Variability analysis will be performed to determine critical points during electric current simulations inside the human head. Problems related with segmentation of MRI scans and electrical properties of the tissues has been confirmed as a main source of the uncertainty. It was shown that different results can have different width and shape of a variational spread.*

***Streszczenie.*** *Numeryczne modelowanie problemów bioelektromagnetyzmu podlega wielu problemom mogących znacząco obniżyć wiarygodność wyników. Analiza wrażliwościowa została wykonana, aby określić zagrożenia występujące podczas stymulacji elektrycznej głowy ludzkiej. Zagadnienia związane z segmentacją skanów MRI i właściwościami materiałowymi tkanek zostały potwierdzone jako źródło silnej niepewności wyników. Pokazano, że różne wyniki mogą mieć różną szerokość i kształt rozkładu zmienności.* ***(Niepewność symulacji numerycznych w problemach bioelektromagnetyzmu)***

**Keywords:** computer modelling, results reliability, bioelectromagnetic problems
**Słowa kluczowe:** modelowanie komputerowe, wiarygodność obliczeń, problemy bioelektromagnetyzmu

## Introduction

Numerical modelling methods, as a imitation of reality, suffers fundamental problems of related with its reliability. Complicated processes such as bioelectromagnetic simulations are essentially vulnerable on this issues. Generally there two types of uncertainties are distinguished [3]:

**epistemic** - lack of knowledge (sometimes referred as a ignorance),

**aleatory** - inherent variations (also called variability).

Since the first one can be reduced by developing more advanced modelling techniques, the second is irreducible. In real, complex simulations both types of uncertainties are mixed and influence reliability of final results. So it is important to identify stages with higher uncertainty which are determining of a whole process accuracy. Especially if they are aleatory, what means that can be eliminated. Reduction of epistemic variation at specific stage of the method is justifiable only is it dominates aleatory factors, otherwise it won't improve total reliability.

Among methods for analysing uncertainties, one the most popular solution is Monte Carlo or similar Latin Hypercube Sampling [3]. Those statistical methods are based on random probing of parameters n-dimensional space. Another view on the problem is presented by interval analysis. The aim of interval analysis is to find lower and upper bounds of possible solutions, so computational complexity is significantly smaller than using Monte Carlo [3][6].

Table 1. Stages of bioelectromagnetic simulation and estimation of related uncertainties.

| stimulation stage | uncertainty type | uncertainty level |
|---|---|---|
| mathematical model | epistemic | very low |
| numerical approximation | aleatory | low |
| geometry | epistemic | medium |
| tissue properties | aleatory | high |

Table 1 presents raw estimation of uncertainties introduced by each stage of bioelectomagnetic simulation. Mathematical models are directly related with knowledge about the phenomenon. Today, physics provides good understanding of field theory, so uncertainty related with mathematical model should be estimated as very low. Numerical approximation creates new group of errors, but they are semi-random by the nature, and can be easily reduced by using higher order description or adaptive algorithms. It could be

Table 2. Low frequency tissues conductivities variability taken from multi-source report [5].

| Tissue cond. $[S/m]$ | avg | std.dev. | min | max |
|---|---|---|---|---|
| Brain (White Matter) | 0.37 | 0.34 | 0.05 | 1.12 |
| Brain (Grey Matter) | 0.19 | 0.1 | 0.08 | 0.26 |
| Bone | 0.1 | 1 | 0.02 | 1.17 |
| Skin | 0.00121 | 0.000078 | 0.00043 | 0.002 |
| CSF | 1.80 | 0.21 | 1.59 | 2.00 |
| Muscle | 0.29 | 0.18 | 0.04 | 0.60 |

assumed that detailed geometry is possible to discover (epistemic), but it is not an easy task since input image resolution is always limited. Even worse is with tissue properties, which variability reaches over 100%. Those aspects are discussed in the next sections of the paper.

Statistical variation of the electrical properties is active subject in bioelectromagnetics. Stochastic FDTD method [11] was developed to deal with this problem. Other authors take Monte Carlo approach to test different material properties [10].

Novelty of this paper lays at combining variation of tissue property with uncertainty of model geometry. As an example, external electric stimulation of the brain is analysed, but the methodology could be easily expanded to other biomedical problems [8].

## Uncertainty of biological models

Biological models are deeply more complex than a typical technical objects. The first source of this difference are properties of biological materials. Physicians distinguish hundreds tissues inside human body, but this is just a begging of complexity. The most of them are inhomogeneous, anisotropic and non-linear. Values can differ for each patient, but also time-variation is observed.

For many years researchers around the globe are struggling with measuring tissue parameters. Our work is based on multi-source summary report prepared in Swiss institute IT'IS published on August 2014 [5]. Authors of this database are constantly doing literature review collecting all tissue measurements. Values of conductivities for electrical stimulation analysis are presented on Fig. 2. One can notice that variation change from 25% for CSF, up to 580% for bones.

Shapes of internal structure of the body is obtained from medical imaging modalities (MRI, CT). Using process called segmentation, tissues regions has to selected on each slice.

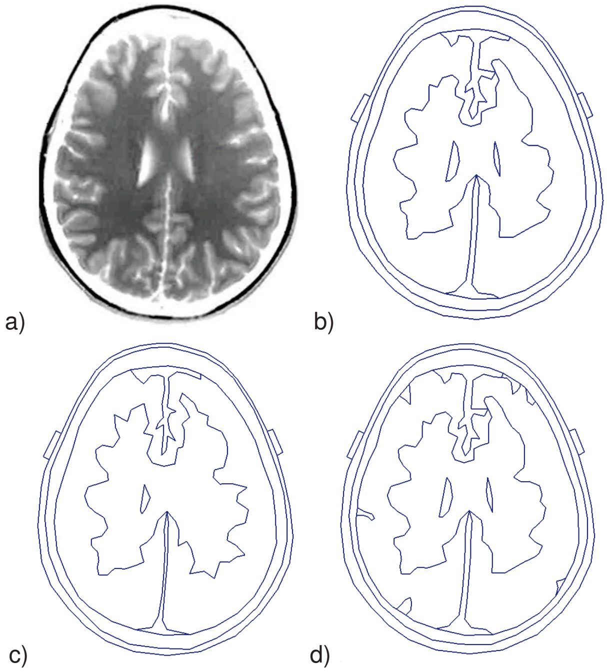



Fig. 1. Tissue recognition is always slightly ambiguous, a) original image, b,c,d) three different segmentations.

As seen on Fig. 1 segmentation is another source of uncertainty. Shapes of the tissues are usually more complicated that model resolution, moreover border line between different tissues could be fuzzy what leads into ambiguous distinction.

### Electric stimulation model

Impact of stochastic approach is demonstrated on the basis of problem of electrical stimulation. Low frequency direct current excitation could be described using simple Laplace equation for scalar potential $\varphi$:

$$\nabla \cdot \sigma \nabla \varphi = 0 \quad (1)$$

In low conducting human body displacement current is negligible [1], so it is allowed to treat conductivity $\sigma$ as a real value.

Current is injected through electrodes expressed as boundary condition. Special attention has to placed to correct modelling of the contact between electrodes and the skin [12].

Electric current conducted through human body is analysed from different perspectives: therapy, safety, diagnostic [4]. Most of them apply 3D anatomically correct models based on scalar potential, as described on eq. (1), for safety validation [2][13]. We are located at another group of applications which are related therapeutic stimulations [9]. Case discussed in this article is Electro-convulsive Therapy (ECT), which is cross skull brain stimulation. ECT problem was chosen as a one especially sensitive to bone thickness, shape and conductivity.

Numerical model is described and solved using finite element methods implemented by Argos2D software [7]. Python scripting and client-server features have been used to manage hundreds of repetitive solutions. Complexity of the mesh in the single solution was reduces to make calculations as short as 5 seconds.

### Variability analysis

Presented model is a subject of variable parameters, so statistical analysis has to be performed to determine distribution of solutions. Five different tissues (see Table 2) were crossed with different segmentations (see Fig. 1) what makes six dimensional space of parameters variability. Each conductivity parameter received three values (minimum, average and maximum). Also three different segmentation was used. That all produce $3^6 = 729$ different cases to be modelled. Our method should be classified as a extended interval analysis, since so there was no random selection of parameters.

To verify whether variability is changeless, three different solutions were investigated. The first one is the total power dissipated inside the brain (white and grey matter). To calculate this value solution of power density is integrated:

$$P = \int_{\text{brain}} \frac{J^2}{\sigma} \mathrm{d}v. \quad (2)$$

The second and the third solutions ($J_1$, $J_2$) are the local values of current density at selected points. Point for $J_1$ is in the center of the head, and point for $J_2$ in the grey matter close to the left electrode (see Fig. 2).

One of 729 modelled cases is presented on Fig. 2. Colour map and vectors describe current density distribution, where current flows from right electrode to the left one.

As mentioned above parameters space is 6-th dimensional, so to visualize distribution of solutions, histogram plots were used as presented on Fig. 3. Ranges for histogram bars were defined as uniform division between minimum and maximum of observed values. See Table 3 to find precise ranges definitions.

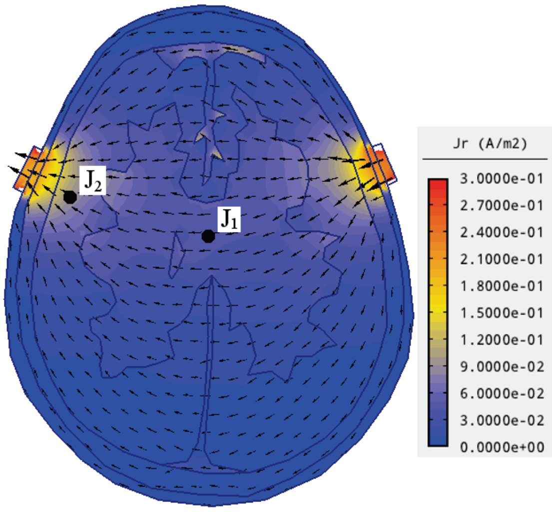
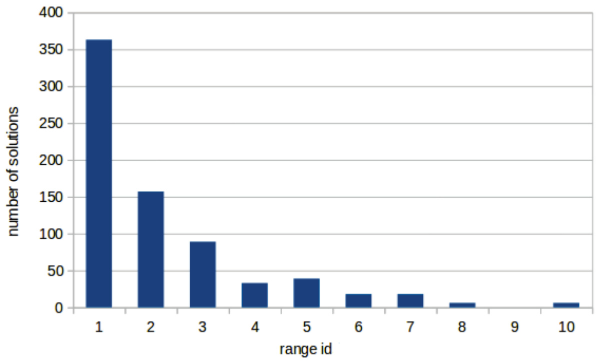



Fig. 2. Exemplary current density distribution. Values at points $J_1$ and $J_2$ are presented at histograms on Fig. 3b),c).

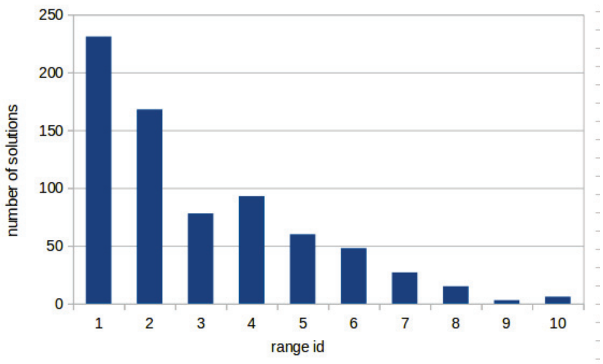
Table 3. Results values ranges for histograms on Fig. 3

| range id | $P[mW]$ | $J_1[mA/m^2]$ | $J_2[mA/m^2]$ |
|---|---|---|---|
| 1 | 0.011–0.22 | 2.5–14 | 9.1–28 |
| 2 | 0.22–0.44 | 14–27 | 28–47 |
| 3 | 0.44–0.66 | 27–39 | 47–66 |
| 4 | 0.66–0.87 | 39–51 | 66–86 |
| 5 | 0.87–1.09 | 51–64 | 86–105 |
| 6 | 1.09–1.30 | 64–76 | 105–124 |
| 7 | 1.30–1.52 | 76–88 | 124–143 |
| 8 | 1.52–1.74 | 88–101 | 143–163 |
| 9 | 1.74–1.95 | 101–113 | 163–182 |
| 10 | 1.95–2.17 | 113–125 | 182–201 |

a) $P$:




b) $J_1$:




c) $J_2$:

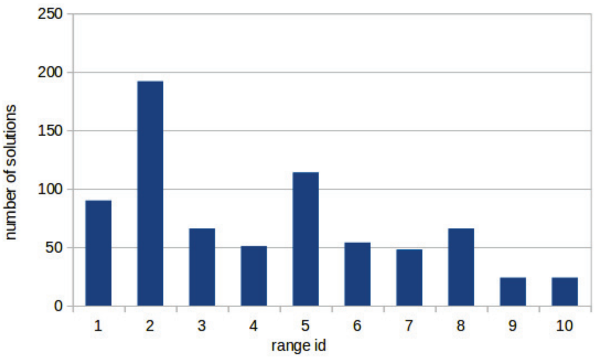



Fig. 3. Histograms of solutions values, a) for total power loses inside the brain ($P$), b) current density magnitude at point $J1$, c) current density at point $J2$. Ranges used in histograms are defined according to the Table 3.

The variability of solutions is definitely very high comparing with typical engineering problems. For total power inside the brain solutions ($P$) are between 0.011 and 2.17 [mW], local current density at point $J_1$ are from 2.5 to 125 [mA/m$^2$], and in point $J_2$ from 9.1 to 201. As one can see variability factor (max/min) reaches 197 for power, 50 for $J_1$ and 22 for $J_2$.

Lets make a closer look on histograms presented on Fig. 3. Each of them has different shape. At histogram a), over 350 of $P$ solutions are located on the first range (0.011–0.22 mW). What means that low values are much more probable. Histogram b) for $J_1$ (current density in the center of the brain) doesn't have only one strong bar. Values are spread mainly over ranges 1 and 2 which have over 370 solutions in total. Histogram c) for $J_2$ (current density near electrode) is nearly flat, what should be understood in a way that all values in ranges have equal chances.


**Summary**

Numerical models of bioelectromagnetic problems are subject of enormous variation of input parameters. Complexity of living tissues shapes and material parameters causes that stochastic approach should be taken.

Variability analysis for numerical simulation of electrical stimulation of human head model has been performed. Five tissues conductivity variation and segmentation fuzziness were considered. Results showed that specific values of current density and dissipated power have wide dispersion range with different shapes of probability. What leads to conclusion that statistical analysis of even simple bioelectromagnetic question can't be avoided.

Further research will be focused on taking into account detailed description of variability function of tissue parameters and geometry. This will significantly increase the number of required analysis, so the importance of the investigations for more efficient methods for variability analysis for 3D, realistic models will be increased.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