Electro-Thermal Model of Liver Tissue and its Approximation

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Abstract. *This paper deals with the proposal of the approximation method of complex organic tissues (in this example liver) for the needs of development finite – element models for investigation of the surgical impacts. The main objective of the proposed approximation is to reduce the required computational power and time for electro-thermal simulations of given tissue, while main aim is to be able to design a relevant 3D objects of tissues which are targeting real dimensions of human organs. The approximated parameters are meant to be used in three-dimensional finite element simulation models, whereby investigation of the electrosurgical impact in the way of current field distribution within tissue is done initially. Verification of proposed approximation is given by the comparison of electrical current distribution within complex model of liver tissue and approximated one, while at the end of the paper the model extension into big scale is being shown.*

Keywords

Electro surgery, finite element method, tissue approximation, tissue modelling.

1. Introduction

Medicine and surgery belong to the scientific areas in which the knowledge, proceedings and devices are updated rapidly. The reason for this development is the fact that characterizes the scientific areas themselves - the requirement of extreme precision and exactness of the processes and tools. Exactly these requirements are the incentive of rapid development of frequently used devices, such as the electrosurgical unit. Despite the rapid progress and implementation of new methods, the use of electrosurgery still brings on many risks for the patient, which could lead to fatal consequences.

Nowadays more than 90 % of all surgical operations utilize electrosurgery. It is also the preferred way of bleeding control in laparoscopy [1] and [2]. This technique offers possibility to cut, coagulate, ablate or desiccate tissue. The first electrosurgical units were used in 1930s; however, their application has risen mostly after the introduction of laparoscopy [3]. It is not to be polemized about the unquestionable benefits of this technique, but it is also extremely important to be aware of the risks the tool is bringing on. For the accurate and secure application of this apparatus, it is inevitable to clarify the causation of risks and conditions of their development, to avoid them, to intervene adequately at their presence and eventually, to minimize their consequences [4].

Despite the fact, that electrosurgery is common method being used for a long time, improved by modernized safety elements, it often induces unpredicted reaction of tissue or organism [5] and [6]. Mechanisms of the complication development, when using electrosurgery, are diverse. The damage during laparoscopy can occur due to incorrect identification of anatomical structures, mechanical trauma or electrothermal complications. The keystone of electrothermal injury can be direct application, insulation failure, direct coupling, capacitive coupling and burns at the site of ECG leads and blood cannulas because of the failure of return electrode. Most of these risks are eliminated by using new methods such as active electrode monitoring system, tissue response monitoring or nanotechnology.

Despite the implementation of mentioned technologies, there is a set of complications, which are internal burns in remote locations and inaccurate cuts in the target tissue. Causations of internal burns in distant site and inaccurate incisions in surgical field are far from clear; consequently, it is very difficult even im-

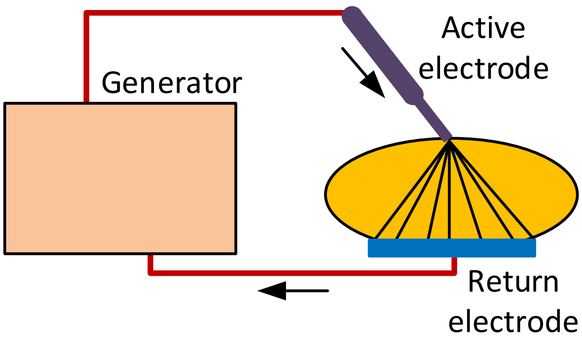

Fig. 1: Principle of configuration for monopolar cutting.

possible to avoid this complication. One of the possible explanations of this phenomenon could be the presence of sneak currents. This term is used in electrical engineering to describe the current traverse out of its optimal path, in another trace. In the field of electrosurgery, the term sneak currents refer to the current traverse through the patient's body, whereby the field is enclosed by alternative trace between the active and indifferent electrode, outside of the target tissue. Consequently, an undesirable injury may develop in the area of higher electrical conductivity in comparison to the conductivity in the operating field.

The paper will describe an approximation method of electro-thermal parameters of organic tissue. This approximation is needed for large-scale simulation of organs and can be used for partial approximation and consequent development of the full-scale human body model. Presented approach can be for the study of the impact of electrosurgery. The approximation is described for main parameters, which are needed for modelling, i.e. electrical conductivity "σ", relative permittivity "ε", thermal conductivity "λ", specific heat capacity "c" and density "ρ". The approximation is valuable due to fact that tissue models present very complex structure of thin layers. Such geometry is too complex for full-scale FEM model development from computational time of view. Presented methodology is accurate compared to complex model and enables investigation of various impacts on the full-scale models of the human body (electrosurgery, electromagnetic field, thermal radiation, etc. . .).

2. Complex Model of Liver Tissue

In this part of the presented article, 2D modelling of liver tissue for purposes of simulation analysis is presented, focusing on the selected segment of liver tissue, sufficiently representing the conditions during the electrosurgical procedures in the liver.

From the electrical aspect, body tissues represent a heterogeneous object consisting of number of basic units-cells. In terms of current flow, the human tissues belong to the group of second-class conductors, which means that a charge transfer is realized by ion transport [7], [8], [9] and [10].

The basic structural component of liver is hepatocyte. Hepatocytes are arranged specifically and in microscope image, they create classical structural units – hepatic lobules.

The presented model of hepatic tissue considers complex structure and its approximated form. As was mentioned, the model represents lobule and has dimensions of 0.7×2 mm. For simplification purposes, the model is divided into sections, while axisymmetric is considered. These sections are:

- vena centralis (A),
- sinusoids with hepatocytes (B),
- interlobular bile ducts with sinusoids (C),
- interlobular bile ducts with arteries and veins (D).

Fig. 2: Complex model of liver tissue.

Tab. 1: Geometrical dimensions of individual building blocks of liver tissue.

Component	Width (mm)	Height (mm)	Number of layers within model
Vena centralis	0.043	0.2	1
Small blood sinusoids	1	0.0007	51
Small bile ducts	0.02	0.002	50
Hepatocytes	1	0.0033	50
Main blood sinusoid (arterie)	0.023	0.2	3
Main bile ducts	0.0276	0.2	2

It might be seen that each section of the tissue represents highly non-homogenous structure, thus very precise modelling was initially done (Fig. 1). Next table (Tab. 1) shows geometrical dimensions with the number of individual building blocks of the tissue model, while Tab. 2. is showing their electrical and thermal properties.

Tab. 2: Electro-thermal coefficients of individual parts of liver tissue.

Component	**Electric conductivity ($\mathbf{S{\cdot}m^{-1}}$)**	**Relative permittivity**	**Density ($\mathbf{kg{\cdot}m^{-3}}$)**
Vena centralis	0.721	4294	985
Small blood sinusoids/ Main blood sinusoid (arterie)	0.721	4294	985
Small bile ducts/ Main bile ducts	1.4	120	982
Hepatocytes	0.12	4032	985
Component	**Thermal conductivity ($\mathbf{W{\cdot}(m{\cdot}K)^{-1})}$)**	**Density ($\mathbf{kg{\cdot}m^{-3}}$)**	**Heat capacity at constant pressure ($\mathbf{J{\cdot}(kg{\cdot}K)^{-1}}$)**
Vena centralis	0.505	985	3470
Small blood sinusoids/ Main blood sinusoid (arterie)	0.505	985	3470
Component	**Electric conductivity ($\mathbf{S{\cdot}m^{-1}}$)**	**Relative permittivity**	**Density ($\mathbf{kg{\cdot}m^{-3}}$)**
Small bile ducts/ Main bile ducts	0.505	982	3470
Hepatocytes	0.565	985	3470

The simulation model aimed at the current distribution within the liver tissue and it has been set for monopolar operational model, which is related to the cutting mode of the electrosurgical generator. The settings are as follows:

- distance between probe and tissue $= 0.5 \cdot 10^{-4}$ m, $2 \cdot 10^{-4}$ m,
- monopolar mode (390 kHz, $U_{pp} = 2300$ V).

3. Liver Tissue Approximation

The proposed approximation assumed the possibility of dividing each type of organic tissue to the level of geometrically regular layers (Fig. 2.) with geometrical parameters (xp_i, yp_i, zp_i). Next assumption defines that for every layer of tissue, specific electro-thermal parameters are given (σ_i, ε_i, λ_i, c_i, ρ_i).

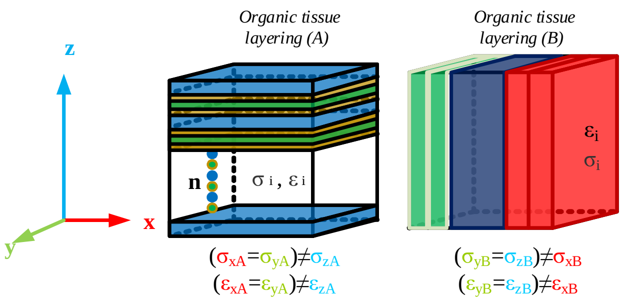

Fig. 3: Layering of organic tissue (generally applicable for all tissue types).

All further derived approximations are based on the conversion of the desired parameter to area (volume) of the given tissue layer. Approximations are based on a calculation of wanted parameter for given area (volume) of the single layer of the tissue. This new area (volume) is specified with the parameter, which is calculated from the individual tissue layer parameters. Their properties are then combined within the common parameter which is relevant for one block, while its value is also dependent on the dimensions (geometry). This approximation needs to be done in three-dimensional space due to differences in tissue arrangement. According to Fig. 2 and based on the relations for the parallel Eq. (1) and serial Eq. (2) impedances, the following approximations for the electrical parameter may apply:

$$\sigma_{xA} = \frac{\left(\sum_{i=1}^{n}\left(N_i \cdot \sigma_i \cdot yp_i \cdot \frac{zp_i}{xp_i}\right)\right) \cdot x}{y \cdot z}, \tag{1}$$

$$\sigma_{xB} = \frac{\dfrac{\prod_{i=1}^{n}\left(N_i \cdot \sigma_i \cdot yp_i \cdot \frac{zp_i}{xp_i}\right)}{\prod_{j=1}^{n}\left(\sum_{i=1,i\setminus i(j)}^{n} N_i \cdot \sigma_i \cdot yp_i \cdot \frac{zp_i}{xp_i}\right)_j} \cdot x}{y \cdot z}, \tag{2}$$

where σ_x is approximated electrical conductivity of parallel (A) and serial (B) layers in x-direction in ($\mathrm{S{\cdot}m^{-1}}$), "n" is number of layer's type, N is number of the same type layers, σ_i is electrical conductivity of given layer, xp_i, yp_i, zp_i are geometrical parameters of layer in (m) and x, y, z are geometrical parameters of approximated block in (m).

Based on the equivalency, other parameters like relative permittivity or thermal conductivity can be calculated with the use Eq. (1) and Eq. (2), while " σ" or "λ" shall be replaced.

The density approximation is given by Eq. (3). This approximation is needed for proper thermal simulation

Tab. 3: Approximated electrical parameters for individual segments of hepatic tissue.

Direction	B		C		D	
	σ (S·m^{-1})	ε (-)	σ (S·m^{-1})	ε (-)	σ (S·m^{-1})	ε (-)
X	0.2277	4092.9	0.8677	2136.9	$2.79 \cdot 10^{-4}$	216.01
X	0.2277	4092.9	0.8677	2136.9	0.7929	2057.3
Z	0.1404	4062.9	0.0019	5870.2	0.7929	2057.3

results.

$$\rho = \sum_{i=1}^{n} \left(\frac{N_i \cdot x_i \cdot y_i \cdot z_i \cdot \rho_i}{x \cdot y \cdot z} \right), \tag{3}$$

where ρ is the density of approximated block in (kg·m^{-3}) and ρ_i is the density of given layer in (kg·m^{-3}).

The last parameter that must be approximated is specific heat capacity given by following equations Eq. (4), Eq. (5) and Eq. (6):

$$c_{xA} = \left(\frac{\sum_{i=1}^{n} N_i \cdot \rho_i \cdot yp_i \cdot zp_i \cdot xp_i \cdot c_i}{\rho \cdot x \cdot y \cdot z} \right), \tag{4}$$

$$c_{xB} = \frac{\dfrac{\prod_{i=1}^{n} \left(N_i \cdot \rho_i \cdot yp_i \cdot zp_i \cdot xp_i \cdot c_i \right)}{\prod_{j=1}^{n} \left(\sum_{i=1, i \setminus i(j)}^{n} N_i \cdot \rho_i \cdot yp_i \cdot zp_i \cdot xp_i \cdot c_i \right)_j}}{\rho \cdot x \cdot y \cdot z}, \tag{5}$$

$$c = \sqrt{c_x^2 + c_y^2 + c_z^2}, \tag{6}$$

where c is specific heat capacity of an approximated block in (J·(kg·°C) $^{-1}$), c_x is approximated heat capacity in the x-direction (J·(kg·°C)$^{-1}$) and c_i is specific heat capacity of given layer (J·(kg·°C)$^{-1}$).

The example of the calculated values of approximated electrical parameters for individual segments of liver tissue are given in Tab. 3.

4. Comparison of Simulation Results from Complex and Approximated Model

The verification of the proposed approximation methodology of the tissue model is done by comparison between two simulation models of the liver tissue.

The first model is a complex model composed of different parts of the liver tissue (Fig. 1). It consists of 4 parts, whereby two of them are characterized by axial direction of layers (A, D) and two of them by the radial direction of layers (B, C). Radial parts are composed of more than 100 thin layers, whereby each axial one consists of more than 20 thin layers. Each layer of individual part has defined its own electro-thermal parameters. Approximated model is also defined with 4 parts, but the electro-thermal parameters are given as tensors in radial and axial direction of the whole part (Fig. 4).

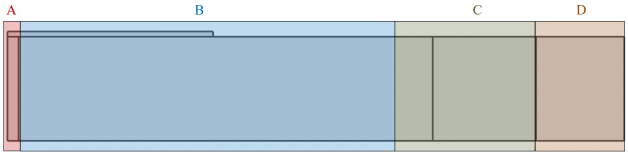

Fig. 4: Geometry of approximated model of liver tissue.

The simulation results of the electric current density are shown both for complex and approximated model in Fig. 6 and Fig. 7 respectively. Variable parameter was distance of the electro scalpel. In the first situation, a direct contact was considered ($0.5 \cdot 10^{-4}$ m), while in the second situation, electrocoagulation was considered ($2 \cdot 10^{-4}$ m).

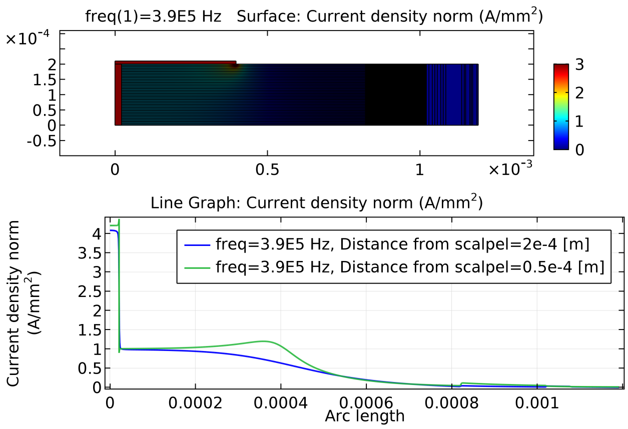

Fig. 5: Complex liver tissue simulation results: current density within the structure (top) and the extraction of the amplitudes of normed current density (bottom).

The results are showing that approximated model shows similar behaviour to the complex model when the value of the current density within individual parts is investigated. The absolute derivation of the results is within interval $\langle 0.5 \backslash 0.25$ A·mm$^{-2}\rangle$, while the eval-

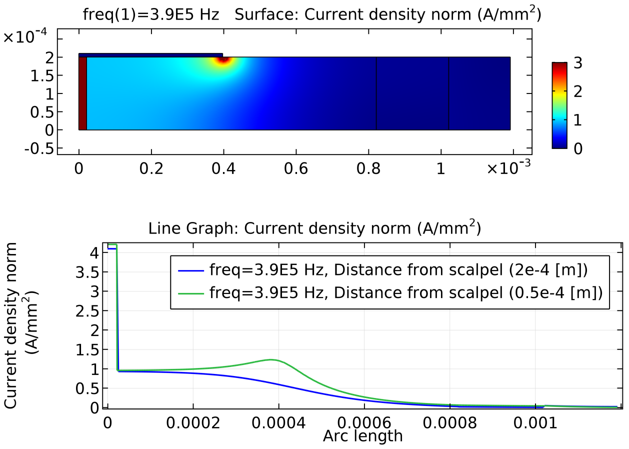

Fig. 6: Approximated liver tissue simulation results: current density within the structure (top) and the extraction of the amplitudes of normed current density (bottom).

uation of this difference within investigated geometry is shown in Fig. 7. It is seen, that higher relative difference is in the case of closer vicinity of the tip of the scalpel.

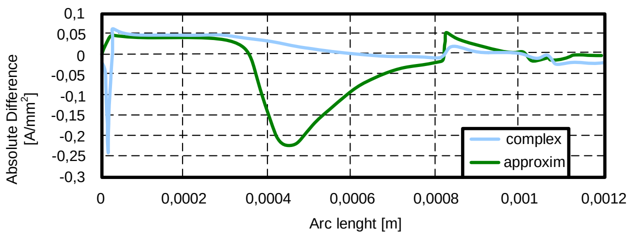

Fig. 7: Absolute difference between complex and approximated liver tissue simulation.

Table 4 is showing computational requirements for both simulation models. It might be seen that approximated model is showing very low requirements on the computational technique and thus computational time is negligible compared to the complex heterogeneous model, thus the potential for further use within more complex analyses cannot be refused.

Tab. 4: Computational requirements for complex and approximated model.

	Solution time (s)	Physical memory (GB)	Virtual memory (GB)	Number of Mesh elements
Hetero-genous	29	3.3	3.85	129703
Appro-ximated	<1	0.915	1.194	4460

5. Model Extension into Complex Structures for Electro-Thermal Impact Investigations

Previous investigation developed approximated simulation model, which accuracy of results is close to complex heterogeneous model. Figure 8 shows the 3D model of hexagonal hepatic structure, which is derived from approximated 2D model. It is seen, that model consists of segments that were previously simplified, and thus segments A – D are implemented. This hexagonal structure can be extended for further use within much bulkier structures, which are relevant to the ratio of real human organ (Fig. 12 right).

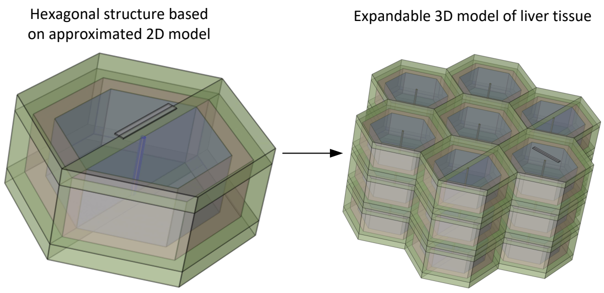

Fig. 8: Approximated 3D model of liver tissue.

The simulation settings for this model are similar to the 2D model, while electrosurgical scalpel is located as is shown in Fig. 9, which shows the visualization of the electric potential distribution within the 3D model of approximated liver tissue.

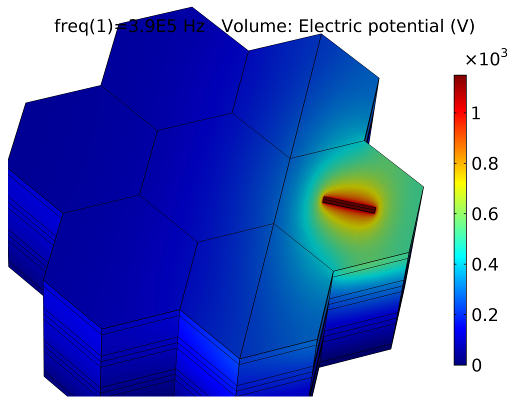

Fig. 9: 3D interpretation of electric potential within 3D single part (left) and extended part of liver tissue (right).

The motivation for which we present the single and multiple 3D model comparison is due to determination of the current density distribution within bulkier samples (Fig. 10).

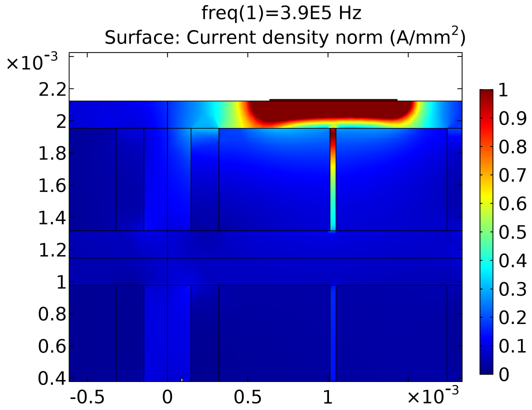

Fig. 10: Distribution of current density within extended part of liver tissue.

Evaluation of the current density in the slice of the structure is performed for the extended part, where the upper right section was selected for comparison (Fig. 11).

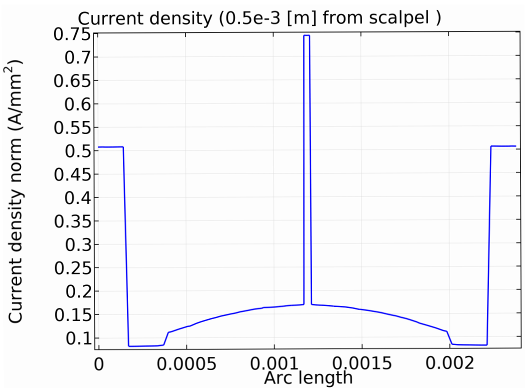

Fig. 11: Current density in slice of the extended part of liver tissue (right).

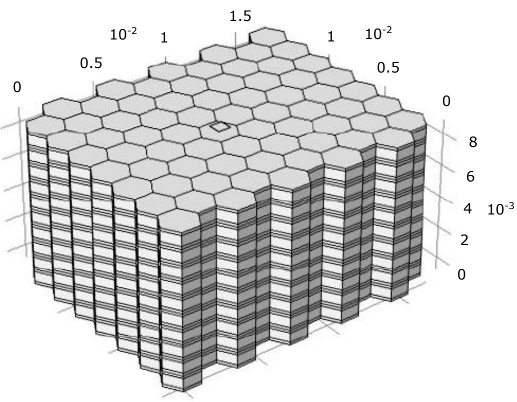

Fig. 12: Expanded model (1.5 mm × 1.5 mm × 1 mm).

The extension of the model was further done for the purposes of more realistic modelling related to the dimensions of the real human tissues (Fig. 12). The results of the current distribution within given volume (1.5 mm × 1.5 mm × 1 mm) is shown in Fig. 13. It is seen, that the current is located at the surface of the tissue in vicinity to the electrosurgical tip. Behaviour is expected and correct [11], [12] and [13], thus it is possible to further provide the thermal simulations in order to find out, how negative is the impact of such surgical procedures.

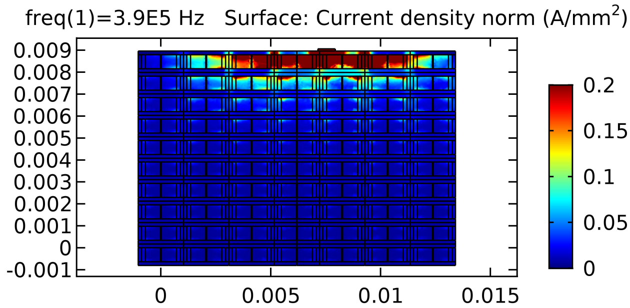

Fig. 13: Current density distribution for expanded model of liver tissue.

6. Conclusions

Previous analysis showed possible negative effects of electrosurgery on the surrounding tissues. The results of simulation experiments proved the increase of current density in the parts of organs distant from the site of surgery. The obtained outcomes show unequal distribution of current lines in heterogeneous tissue; therefore, they provide important information about the risks resulting in the application of this method during the surgical procedures on liver. Because for future works more complex models will be investigated on the level of the real physical dimensions of human organs, the optimized model has been developed. The main purpose is to reduce the computational time and requirements for the complex analyses. At the same time. a high level of accuracy must be achieved. Initially, we found a good match between complex and simplified solution. There is a visible deviation when structured segments of tissue are considered, however still at the acceptable level. On the other side, computational time and computational requirements have been reduced significantly, thus potential of the proposed model is high. Further works will focus on the implementation of thermal behavior within the proposed model and consequently, optimizations of the electrosurgical equipment will be considered too, in order to lower potential damage to human body.

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