Multidisciplinary approach for investigation of injury formation in sensitive tissue structures

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ABSTRACT

In this paper the method of human organ (liver tissue) modelling in the COMSOL environment is presented. Mentioned problems are motivated by the occurrence of negative events during operations utilizing electrosurgery in the tissues with high level of heterogeneity, in particular, the emergence of peroperative complications within abdominal operations. The proposed model of hepatic tissue (respecting its heterogeneous character up to the microstructure of hepatic lobulus) is used for analysis of current field distribution within this tissue. Both complex model of tissue structure (respecting heterogenous structure) and approximated model are mutually compared. The obtained results are exploitable for the analysis of probability of injury formation in sensitive tissue structures, while approximated model shall serve for optimization of complex and time consuming analyses.

Keywords: electrosurgery, electrocoagulation, electrocautery, sneak currents

1. INTRODUCTION

Medicine and surgery belong to the scientific areas in which the knowledge, proceedings and devices are updated rapidly. The reason of 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 of 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, 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 of 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, 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 the use of new methods such as active electrode monitoring system, tissue response monitoring or nanotechnology.

Despite of 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 impossible to avoid this complication. One of the possible explanations of this phenomenon´s 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 other trace. In the field of electrosurgery the term sneak currents refers 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.

In this paper, we would like to compare simulation results of the current field distribution within the complex heterogenous model of the tissue and its simplified approximated replacement. In future, such approach is usefull and necessary when negative effects on human tissues are investigated. Thus v**irtual simulation model, respecting the real characteristic of human tissue is the most acceptable and ethical method for the analysis and evaluation of the electrosurgical instruments.** Therefore, we would like to present the methods of sneak current field analysis being one of unfavourable side effects of electrosurgery.

2. CHARACTERISTICS OF HEPATIC TISSUE

Body tissues represent, from the electrical aspect, a heterogeneous object consisting of number of basic units-cells. In terms of current flow, the tissue is second-class conductor, which means that a charge transfer is realized by ion transport. Organs of the human body are formed by variously arranged cells with various biological and electrical characteristics. Besides, some cells are organized in specific form creating characteristic zones of an organ. By visual demonstration, this can be seen in liver, which due to its detoxifying, eliminating and secretory function is one of the most important organs of the human body.

The basic structural components of liver are hepatocytes. Hepatocytes are arranged specifically and in microscope view, they create classical structural units- hepatic lobules. Hepatic lobule represents a polygonal tissue mass of approximately 0.7 x 2 mm. Within the liver lobule, hepatocytes are arranged radially, producing a layer of one or two cells leading from the periphery towards the centre. The liver lobule structure is shown in the following figure (Fig 1.)

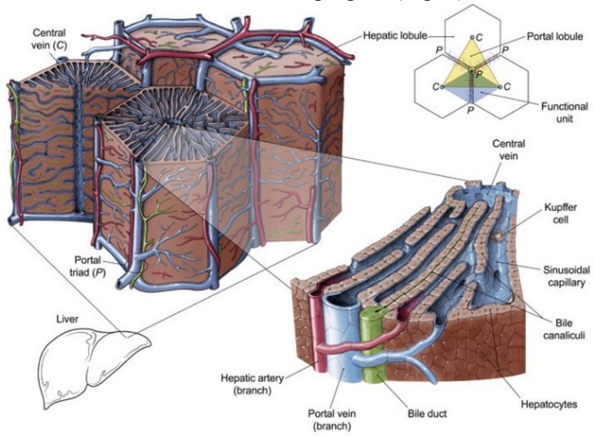

Fig. 1. The structure of liver lobule (from Illumination studios [7])

3. MONOPOLAR CUTTING MODE

Electrosurgery is the application of a high-frequency (radio frequency) alternating polarity, electrical current to biological tissue as a means to cut, desiccate, coagulate or fulgurate tissue. Its benefits include the ability to make cuts with limited blood loss. Electrosurgical devices are frequently used during surgical operations helping to prevent blood loss in hospital operating rooms or in outpatient procedures.

There are two different ways of electrical schemes used in the electrosurgical units, namely the monopolar and bipolar mode. Monopolar mode is the most frequently used mode and at the same time the mode with high risk of injury creation. For this reason, the monopolar mode will be concerned further on.

In monopolar electrosurgery, tissue is cut and coagulated by completing an electrical circuit that includes a high-frequency oscillator and amplifiers within the electrosurgical unit, the patient plate, the connecting, cables, and the electrodes (fig. 2). In most applications, electric current from the electrosurgical unit is conducted through the surgical site with an active cable and electrode. The electrosurgical current is then dispersed through the patient to a return electrode returning the energy to the generator to complete the path.

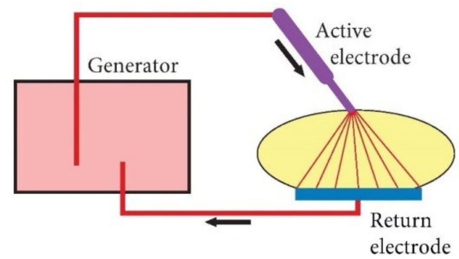

Fig. 2. Priciple of configuration for monopolar cutting

Monopolar electrosurgery has the means of delivering energy to the tissue through several modalities (modes of operation): pure cut, blended cut, desiccation (or pinpoint), and spray (or fulguration). The delivery system of the monopolar electrosurgical generator can be a hand controlled pencil (reusable or disposable) or a foot controlled pencil. A number of accessories can be adapted to the foot control output jack to deliver energy through a number of instruments.

4. HETEROGENEOUS MODEL OF HEPATIC TISSUE FOR ELECTRICAL MODELING

Basing on the abovementioned information, so-called geometrical model has been created, which 2D setting represents the Fig.3. The simulation model represents hepatic tissue in close contact with active electrode. Centrally, there is hepatic lobulus with the dimensions of 2x2mm. Heterogeneous character is created by biliar-vascular bunch, situated along the both sides of lobulus, consisting of 1 branch of vena portae, 2 interlobular arteries and 2 interlobular biliary ducts. Introduced model has been created according to the data from survey published by James M. Crawford, Yale University School of Medicine [8].

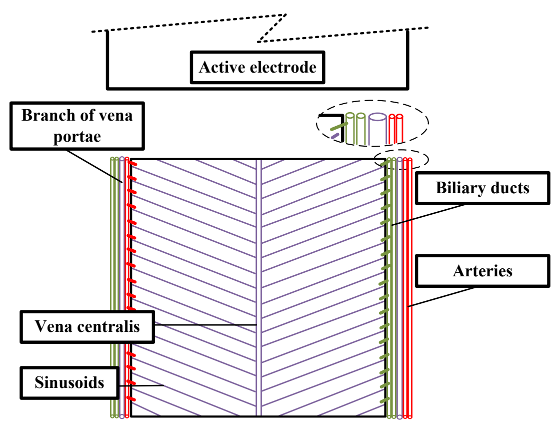

Fig. 3. Simplified geometric model of hepatic tissue in 2D setup

Dimensions of single elements in portobiliary area have been ascertained in our statistical analysis of geometric dimensions of hepatic tissue histological slides, presented in online database [9]. The average geometric dimensions of biliar-vascular bunch have been obtained in the picture analysis of each histological slide, results are presented in the Table 1. In order to determinate electrical parameters the software presented on the web site of Institute for applied physics, Florence, Italy [10] has been used. The relevant parameters extracted for further simulation are shown in the Table 2.

TABLE I. Average geometrical proportions of single elements

	Arteriole	Venule	Bile duct	Vena centralis
average external diameter [μm]	23,33	68,87	27,6	42,87
average internal diameter [μm]	13,8	52,07	11	------
wall thickness [μm]	9,53	16,8	16,6	------

TABLE II. Electrical parameters of single elements

Tissue	Frequency [Hz]	Conductivity [S/m]	Relative permitivity
Blood	300 000	0,721	4694,9
Blood vessel	300 000	0,32207	426,06
Bile	300 000	1,4	120
Liver	300 000	0,1225	4032,9

TABLE III. Percentage of hepatic component abundance

Component	Percentage
Vena centralis	9,7%
Blood sinusoids	7,72%
Bile ducts	7%
Hepatocytes	75,58

The percentage of each component in hepatic tissue represents the last step to create a geometric model of liver. After the implementation of all the above-mentioned data, a definitive model of hepatic lobule has been created, that has been consequently used in the setting of FemLab-Comsol software.

5. MODEL DEVELOPMENT FOR ELECTROSURGICAL ANALYSES

In this article, we present 2D modeling of liver tissue for purposes of analysis, 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 conductor, which means that a charge transfer is realized by ion transport [1].

The basic structural component of liver is hepatocytes. Hepatocytes are arranged specifically and in microscope image they create classical structural units- hepatic lobules. Hepatic lobule represents a polygonal tissue mass of approximately 0.7 x 2 mm. Liver tissue is consequently build from arrangement of lobules.

FEM model of liver lobule

The presented model of hepatic tissue considers complex structure and its approximated form. As was mentioned, the model represents lobule has dimensions of 0,7 x 2 mm. For simplification purposes, the model is divided into sections, while axisymmetric is considered. These sections are:

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

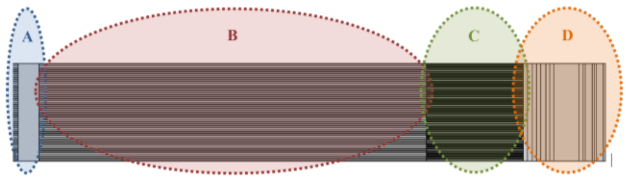

Fig. 4. 2D – Axisymmetric simulation model of hepatic lobule respecting the electrical heterogenity of tissue. Width of excision is 1,2 mm; height is 0,24 mm.

It might be seen that each section of the tissue represents highly non-homogenous structure, thus very precise modeling was initially done (fig. 4). Next table (table 4) shows geometrical dimensions with the number of individual building blocks of the tissue model, while table 5 is showing their electrical properties.

TABLE IV. Geometrical dimmensions of individual bulding blocks of liver tissue

Component	**Width [mm]**	**Height [mm]**	**Nr. 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

Consequently approximated model was done (fig. 5), while approximation in axial and radial direction have been realized and implemented within model structure.

Fig. 5. 2D – Approximated simulation model of hepatic lobule. Width of excision is 1,2 mm; height is 0,24 mm.

TABLE V. Geometrical dimmensions of individual bulding blocks of liver tissue

Component	Electric conductivity [S/m]	Relative permittivity	Thermal conductivity [W/(m.K)]	Density [kg/m3]	Heat capacity at constant pressure [J/(kg.K)]
Vena centralis	0,721	4294	0,505	985	3470
Small blood sinusoids/ Main blood sinusoid (arterie)	0,721	4294	0,505	985	3470
Small bile ducts/ Main bile ducts	1,4	120	0,505	982	3470
Hepatocytes	0,12	4032	0,565	985	3470

The simulation models were practically realized with the use of COMSOL software. Model also considers surrounding air and steel cutter (probe of the electrosurgical generator). In next chapter the operational condition, at which simulation experiments have been realized are described.

6. SIMULATION RESULTS FOR HETEROGENOUS AND APPROXIMATED MODEL

Due to the heterogeneous histological structure of the organ, areas with various electrical resistance values are formed; therefore, the current line distribution will not be regular. In the areas with lower value of resistance, the current density will increase and reversely: in the areas with higher value of resistance, the current density will decrease. Consequently, inhomogeneous current field can cause local damage in the areas with a higher intensity of current flow. Because modelling of the tissue considering its heterogeneity presents very complex and difficult task for simulation of bigger surfaces and volumes, the approximated model have been also investigated, while mutual comparisons of the results are given. Advantage of simplified model is it possibility for further use within development of much more complex simulation models, which shall be close to the real physical dimensions of investigated organs.

The simulation of the current distribution within the liver tissue has been performed 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 mm,
- Monopolar mode (390 kHz, U_{pp} = 2300 V)

Above mentioned settings have influence on the current density concentrated inside the individual parts of the tissue. As was already mentioned, the proposed approach of the modelling could enable to understand which parts are mostly harmed or damaged during operation. Consequently, optimization procedures for such complex devices, as the electrosurgical generator, can be realized. If simplified model show acceptable accuracy to complex model (relative error max. 10%), then save of computational time and rapid prototyping can be expected.

Simulation results for heterogenous structure

The initial experiment with distance of probe equal to 0 mm and with location over vena centralis was performed with heterogeneous structure. Fig. 6 shows current density within the cut of the hepatic lobule and current distribution in graphical form. The main point of this interpretation is to have clear overview, of the amount of current, which is distributed within individual structures of the tissue. It is seen that the highest amount of current density is concentrated within central part of the liver lobule, and is decreasing within radial structure of the tissue. It is caused due to arrangement and electrical properties of the tissue.

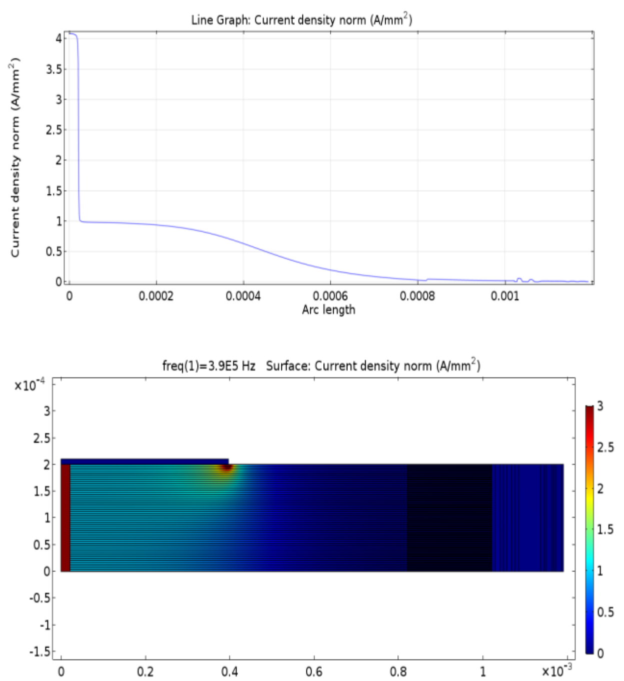

Fig. 6. Current density distribution (top) and streamline current density (bottom) in liver tissue at d=0 mm, hetergenous complex simulation model

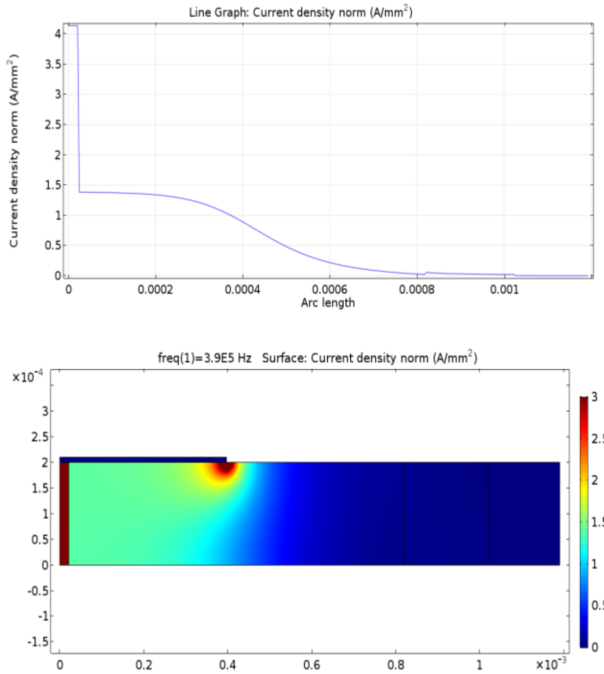

Fig. 7. Current density distribution (top) and streamline current density (bottom) in liver tissue at d=0 mm, approximated simulation model

Fig. 7 shows similar simulation experiment which is presented at fig. 6 but with optimized geometry of the hepatic tissue. Thus simplifications have been considered within several parts of lobule (fig. 4) and parts A – D have predefined electrical conductivities in axial and radial direction, which were established based on approximation methodology. It might be seen, that the current distribution is very similar to the complex model. The only visible difference is for B part of the tissue, where higher amount of the current density is concentrated. This is due to complex structure with B part, and due to simplification of the geometry. However, the results can be acceptable, if some more optimization is done for this part. Possible way can be consideration of tolerance, or integration of offset before computation starts. The relative errors and parameters from the simulation are listed below.

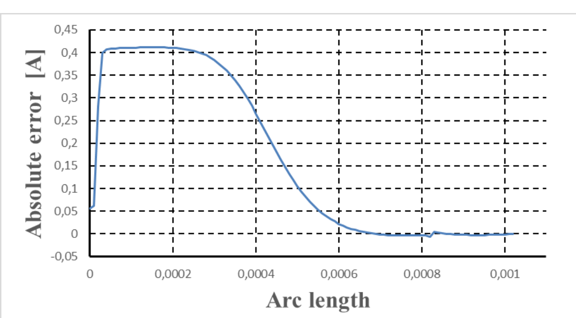

Fig. 8. Current density distribution (top) and streamline current density (bottom) in liver tissue at d=0 mm, approximated simulation model

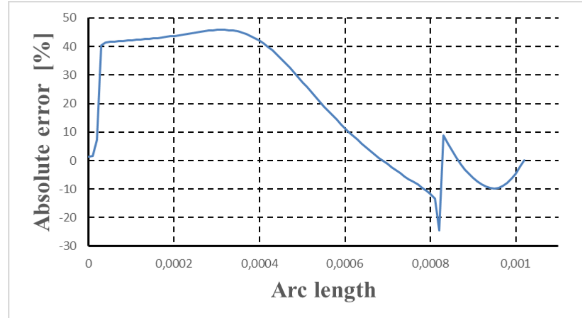

Fig. 9. Current density distribution (top) and streamline current density (bottom) in liver tissue at d=0 mm, approximated simulation model

Table 6 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. Even relative error is 40 % for simplified model the potential for further use within more complex analyses cannot be refused.

TABLE VI. Computational requirements for complex and simplified model

	Solution time [s]	Physical memory [GB]	Virtual memory [GB]
heterogenous	29	3.3	3.85
approximated	<1	0.915	1.194

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 form the application of this method during the surgical procedures on liver. Based on the simulation it is clear, which section of hepatic tissue covers the highest current density. It can be said, that frequently these sections are exposed to the abovementioned phenomena and represents the critical zones which can be potentially damaged. Because for future works more complex models will be investigated on the level of the real physical dimensions of human organs, the optimized model have been developed. Main purpose is to be able to reduce computational time and requirements for the complex analyses. Also high level of accuracy must be achieved. Initially we found good match between complex and simplified solution. Even there is 40% relative error, this value can be further optimized with the implementation of the predefined offset for critical parts of liver tissue. Finally, computational time and computational requirements have been reduced significantly, thus potential of proposed model is definitely high.

Acknownledgement

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