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Methodology for EIT image reconstruction of brain tissue

Abstract. *The aim of this paper is to map in detail the influence of local brain tissue conductivity changes on measured potentials. Based on this study, the methodology and algorithm for an effective determination of corresponding head tissue changes is formulated. Some illustrative examples of local conductivity changes detection are presented.*

Streszczenie. *W artykule przedstawiono metodykę i algorytm określania rozkładu konduktywności elektrycznej tkanek głowy na podstawie rozkładu potencjału mierzonego na powierzchni skóry. Zaprezentowano też kilka przykładowych lokalnych zmian konduktywności i dokładność ich detekcji.****(Metodyka rekonstrukcji obrazu w impedancyjnej tomografii tkanek mózgu)***

Keywords: Electrical Impedance Tomography, image conductivity reconstruction, potential distributions.
Słowa kluczowe: Elektryczna Tomografia Impedancyjna, rekonstrukcja rozkładu przewodności, rozkład potencjału

Introduction

At the present time there are a large number of different sophisticated numerical methods of the image reconstruction of biological tissues in the human body. Modern methods, along with the necessity to secure an exact and detailed spatial localization of an injury (with the minimal time intake of the research performance), must provide the possibility of supervision of the tissues status dynamics during a long time. One of these methods is the method of Electrical Impedance Tomography (EIT).

Electrical Impedance Tomography is a method of image reconstruction of an object internal structure using its spatial distribution of conductivity. The theoretical background of EIT is presented in [1]. There are also other medical systems like X-ray, CT, MRI and Ultra Imaging, which create a 2D image of the object on the basis of density distribution in the living tissue. However, EIT has certain advantages over these systems. It is inexpensive, easy to operate, and it offers the possibility to work virtually in real time.

As described in the sections above, the principle of EIT image reconstruction is based on the evaluation of physical properties of the investigated object, namely on assessing the distribution of electrical conductivity inside the object. The internal conductivity distribution is recalculated from the measured voltages on the electrodes attached to the surface of the object by injecting small amounts of electric current (1−10 mA). Each local conductivity change inside the object causes electric potential changes on the surface of this object. This information about tissue conductivity changes is very useful and important for diagnostics in clinical medicine and also for the therapy related to clinical problems such as pulmonary emboli, breast cancer, cardiac disorder, blood circulation disturbance, and the disturbance of heart function (brain tumours, intracranial hemorrhage, blood clot).

Recently described methods of EIT image reconstruction are mainly based on the deterministic approach [1, 3]. Better image reconstruction results can be reached when an additional technique is introduced, for example the level set method (LSM) [4 – 6].

This paper considers the influence of local head tissue conductivity changes on measured potentials. Based on this study, we formulated the methodology and algorithm of internal conductivity distribution for imaging tissues of the head and for determining the relevant brain tissue changes (intracranial hemorrhage, blood clot) as well as skull trauma. Also, certain results obtained on the basis of image reconstruction were presented.

The basic theory

Different mathematical methods are used to determine the desired spatial distribution of physical parameters inside the object from the measured values of voltages and currents on its surface. Usually, a set of voltage measurements is acquired from the boundaries of the determined volume whilst the object is subjected to a sequence of low-frequency current patterns, which are preferred to direct current ones to avoid polarization effects. Since the frequency of the injected current is sufficiently low (generally in the range of 10−100 kHz), EIT can be treated as a quasi-static problem. Thus, we only consider conductivity σ for simplicity. Therefore, scalar potential U can be introduced; the resulting field is conservative and the continuity equation for the volume current density can be expressed by potential U

$$(1) \quad div(\sigma grad U) = 0 .$$

Equation (1), together with the modified complete electrode model equations [7], is discretized by the Finite Element Method (FEM) in the usual way. Using the FEM, we calculate approximate values of electrode voltages for the approximate element conductivity vector σ (NE x 1); NE is the number of finite elements. Furthermore, we assume the constant approximation of conductivity distribution σ on the finite element region. The forward EIT calculation yields an estimation of the electric potential field in the interior of the volume under certain Neumann and Dirichlet boundary conditions.

The image reconstruction of EIT is an inverse problem of EIT. The aim is to find the unknown conductivity distribution inside the investigated object. In mathematical terms, the inverse problem can be represented as a minimization of the suitable objective function $\Psi(\sigma)$ of σ. In order to minimize function $\Psi(\sigma)$, a deterministic approach based on the method of least squares [1, 2] can be used. Back image reconstruction is a highly ill-posed inverse problem, and therefore it is necessary to apply regularization. There are different regularization methods; one of them is the Tikhonov Regularization method (TRM) [1, 8]

$$(2) \quad \min_\sigma \Psi(\sigma) = \min_\sigma \left[\frac{1}{2} \Sigma \left\| U_M - U_{FEM}(\sigma) \right\|^2 + \alpha \left\| L\sigma \right\|^2 \right].$$

Here, σ is the volume conductivity distribution vector in the object, U_M is the vector of measured voltages on the boundary, and $U_{FEM}(\sigma)$ is the vector of computed peripheral voltages relative to σ, which can be obtained using

the FEM; α is a regularization parameter and L is a regularization matrix. A detailed description of procedures enabling us to find the solution of (2) by the help of the Newton-Raphson method is presented in [1].

Although the stability of this algorithm is slightly sensitive to the setting of initial values of conductivity σ_0, it is very sensitive to the optimal choice of parameter α, which provides balance between the accuracy and the stability of the solution. However, it is likely to be trapped in local minima; therefore, an additional feasible tool must be taken into account to help obtain a stable solution with the required higher accuracy of the reconstruction results. The best reconstruction result will be obtained applying an additional technique such as the LSM.

Influence of conductivity changes on the potential

Electrical impedance values of biological tissues depend on the tissue dimension, internal structure, and arrangement of the constituent cells. Therefore, knowledge of the distribution of electrical properties (such as electrical conductivity) inside the human body can provide useful information about the state of a tissue (changes in heterogeneous structures of the tissue or in its physiological states and functions). The performed tests of electrical conductivity in tissues showed that there is a difference in the conductivity of a normal and a fatigued tissue; the same result also applies to a healthy and a pathologic tissue [9, 10].

The main goal of an image reconstruction is to identify the location and the geometry of regions with a conductivity change and to define the value of this changed conductivity. The common TRM can be used to reach only a rough estimate of the regions mentioned. In many cases, this can be a serious problem as the regions with the above-noted conductivity changes can be very small; therefore, a successful reconstruction requires a finite element mesh with a very high density (a large number of unknowns). This means that, in applying the process of image reconstruction only based on the TRM, it is difficult to achieve the necessary accuracy and stability (it is difficult to assert that the measurement results are objective). For that reason, the reconstruction process was carried out using an additional method (the LSM) during the iteration process. Then, the TRM was applied again to specify the conductivity values, but only inside the limited regions with non-homogeneity.

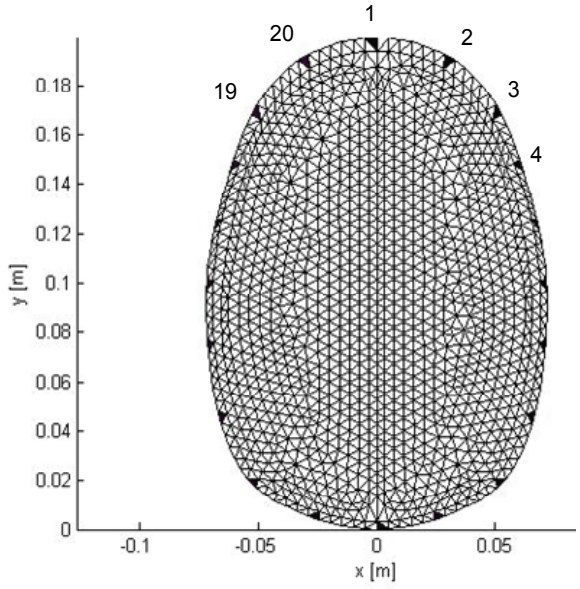

Fig.1. A 2D FEM model for the modelling of brain tissue

The following examples demonstrate the results obtained using the foregoing combination of two methods (the TRM and the LSM), on the condition that the geometry and values of a healthy tissue conductivity are known and complemented with the knowledge of the way a particular disorder affects the tissue conductivity.

The numerical simulation results were obtained using a 2D FEM model, which represents a simplified horizontal slice of the human head, namely scalp, skull and brain (grey matter and white matter). This FEM model consisting of 2360 elements and 1237 nodes is shown in Fig. 1. Twenty electrodes have been used for the voltage measurement on the boundary of the investigated object.

The model of 2D arrangement with the original conductivity distribution (Fig. 2a) was used to simulate voltage U_M. It is a simplified model of the head, which consists of just four homogeneous isotropic layers: scalp, skull, gray and white matter. Therefore, it is necessary to know only the values of average regional conductivities.

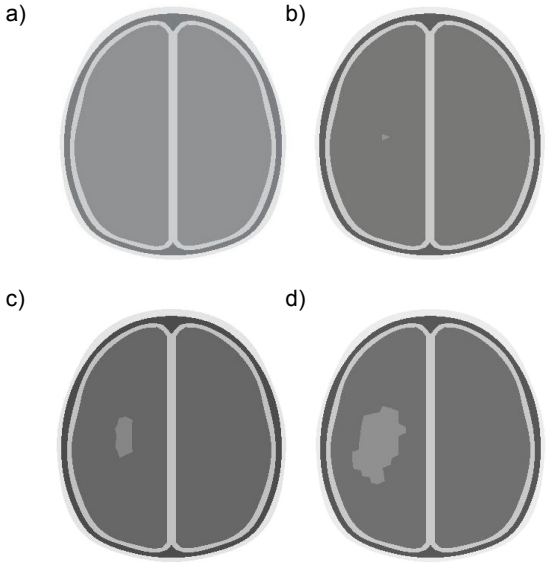

Fig.2. The arrangements of healthy tissue a) and of three sick tissues with different size of blood clots: b) 1 element, c) 24 elements, d) 120 elements

Although each of these values has been measured experimentally [11 – 13], the limited number of measurements and the large variability in the data for all the tissues (excepting the gray and white matters) make it desirable to measure the regional head tissue conductivities in vivo for individual subjects. The conductivity values of different biological tissues used for the following simulations are presented in Table 1; these values were adopted from literature previously published on the topic.

Table 1. The conductivity values of biological tissues

Tissue name	Conductivity [S/m]	References
Scalp	0.435	[14]
Skull	0.087	[14]
Grey matter	0.352	[15]
White matter	0.147	[15]

Figs. 2b to 2d show numerical models which represent different sizes of a tissue defect, namely blood clots. The conductivity of the inhomogeneity subregion representing a blood clot is 0.225 S/m [16]. These inhomogeneities are supposed to be inside the white matter region, right hemisphere. Their size is given by the number of elements: 1 element in Fig. 2b, 24 elements in Fig. 2c and 120 elements in Fig. 2d.

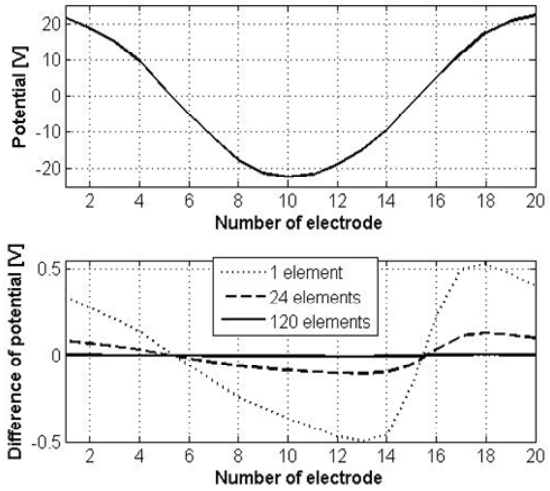

Fig.3. Potential distributions on the head surface for a healthy tissue (top) and for a tissue with blood clots, depending on the size (bottom)

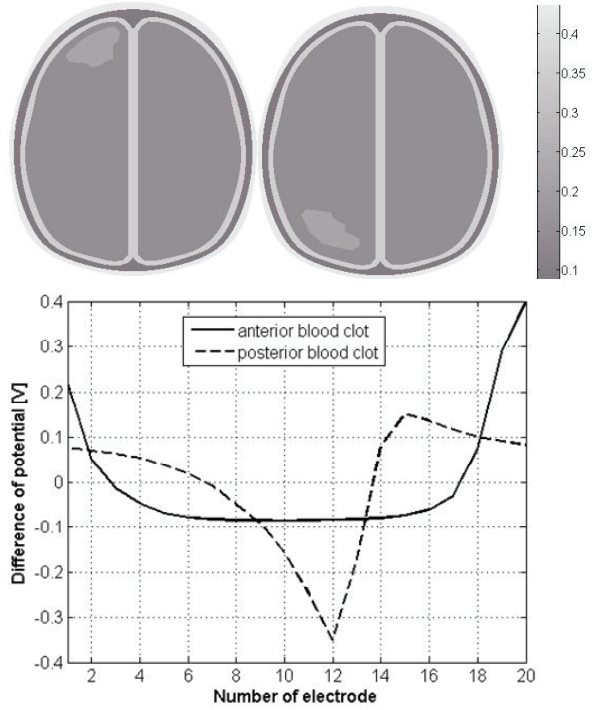

Fig.4. Arrangements with anterior and posterior locations of blood clots and the corresponding differences of potential

The potential distribution on the electrodes for a healthy tissue is shown in Fig. 3, top section. The differences between these values and potential values obtained for a sick tissue with blood clots of different sizes are presented in the bottom part of Fig. 3. We can see that the highest difference corresponds to the size of the defect. The difference was reached on the electrodes placed on the right side of the head model; it corresponds to the location of this defect.

The following arrangements for blood clot detection can be seen in Figs. 4, 5 and 6. Here, the blood clot is assumed to be inside the white matter region again. All blood clots have the same size of 50 elements; however, each clot shows a different location. These figures also show the corresponding potential differences on the electrodes. If we know the potential difference between potential distributions related to a healthy tissue and a sick tissue, we can estimate the rough location of an inhomogeneity and thereby reduce the number of elements with unknown conductivity.

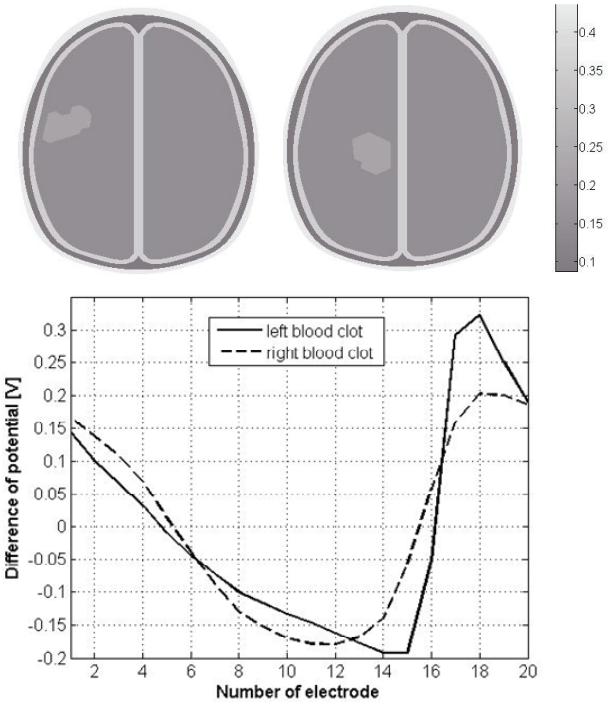

Fig.5. Arrangements with left and right locations of blood clots and the corresponding potential differences

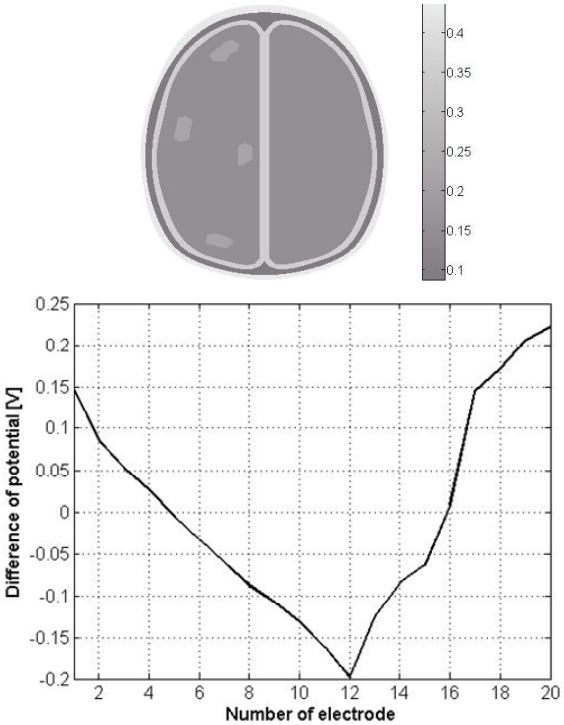

Fig.6. An arrangement with four locations of blood clots and the corresponding potential difference

All the above-presented models with a different arrangement of blood clots were used for the testing of conductivity reconstruction. For the solution of an inverse problem, the Tikhonov regularization method was applied together with the level set method. In order to obtain useful

reconstruction, it was necessary to set parameter $\alpha = 5 \cdot 10^{-6}$ and parameter $d\alpha = 0.3$. All reconstructions were successful and each iteration process ended when the objective function was equal to $\Psi(\sigma) = 3 \cdot 10^{-11}$.

The last example of the skull cracks influence on the distribution of potential is demonstrated in Fig. 7. The conductivity of the region representing skull cracks corresponds to the zero value of conductivity.

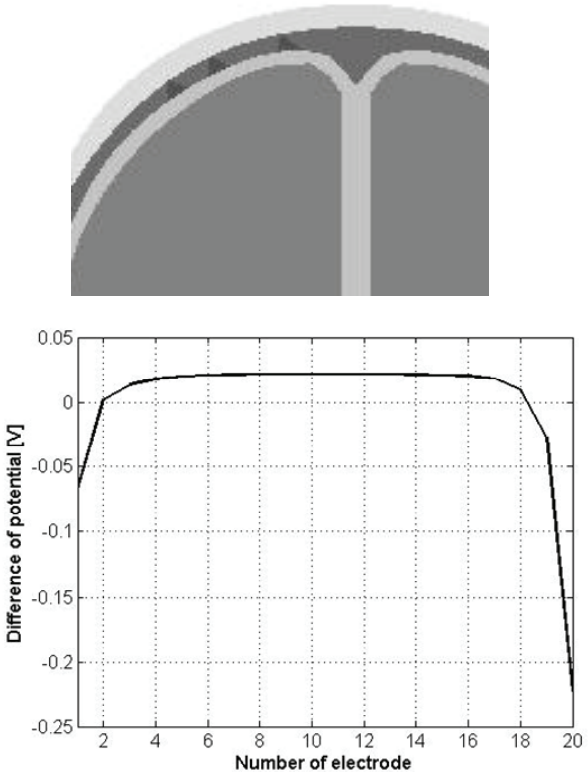

Fig.7. An arrangement of three cracks in skull tissue and the corresponding potential difference

It is evident from the results that the highest values of potential differences are on the electrodes which are very close to the cracks.

For each foregoing example, after the reconstruction process, we obtained the same conductivity distributions as original ones.

Conclusion

In this paper, the influence is examined of head tissue conductivity defects (blood clots and skull cracks) on the distribution of potential over the surface of the head. It is obvious from the performed simulations that the distribution depends on the size and location of the nonhomogeneties (defects). The appreciable number of realized numerical tests shows that the potential difference between potential distributions in a healthy tissue and a sick tissue enables us to determine the rough location of the nonhomogeneties and to estimate their size. Thereby, we can reduce the number of elements with unknown conductivity. These results are used for a significant simplification of the reconstruction process and for saving the time necessary to materialize the solution.

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