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Monitoring brain damage using bioimpedance technique in a 3D numerical model of the head

Rotem Cohen [a], Shimon Abboud [a,*], Marina Arad [b,c]

[a] Department of Biomedical Engineering, Tel-Aviv University, Israel
[b] Department of Geriatric Rehabilitation, Sheba Medical Center, Tel-Hashomer, Israel
[c] Sackler Faculty of Medicine, Tel Aviv University, Israel

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ABSTRACT

Disturbance in the blood supply to the brain causes a stroke or cerebrovascular accident. This can be due to ischemia caused by blockage (thrombosis, arterial embolism) or a hemorrhage. In this study, the feasibility of basic electrical impedance technique for monitoring such damage was analyzed using a computerized model. Simulations were conducted on a realistic 3D numerical model of the head. Tissues were assumed to act as linear isotropic volume conductors, and the quasi-static approximation was applied. Electrical potentials were calculated by solving Poisson's equation, using the finite volume method and the successive over relaxation method. Left–right asymmetry was calculated for several conductivities and volumes of the damaged region. The results were compared with the left–right asymmetry in a head model with normal brain. A negative asymmetry was revealed for blockage (i.e. the potential amplitude over the ischemic hemisphere was greater than that over the intact hemisphere). In case of hemorrhage, a positive asymmetry was found. Furthermore, correlation was found between the location of the damaged region and the electrodes with significant asymmetry.

The 3D numerical simulations revealed that the electrical conductivity and the size of the damaged tissue have an effect on the left–right asymmetry of the surface potential.

1. Introduction

Stroke is one of the leading causes of death worldwide and a significant economic burden to society [1,2]. Better screening tools for stroke patients are constantly being sought to improve patient selection and referral for rehabilitation. Particularly, it can be used to determine "rehabilitation potential", which predicts the length of stay in rehabilitation facilities and the human and material resources required [3–6]. Clinical and imaging variables have been shown to have poor predictive value for recovery potential in stroke patients; therefore, assessment tool such as EEG and functional independence measure (FIM) is being examined in order to predict functional outcome [3,4,7–9].

The bioimpedance technique, in which information regarding the intrinsic electrical properties of biological tissues is assessed by means of applying electrical current to the tissue and measuring the developing surface voltages, seems to be suitable as a modality for brain damage monitoring [10–16]. Several modalities of injected current impedance techniques for brain injury are being used: the basic electrical bioimpedance (EBI) [17–19]; the electrical impedance spectroscopy (EIS) [20–22] and the electrical impedance tomography (EIT) [23–25]. In the EBI technique, an electric current at a single frequency is injected through a pair of electrodes, and the voltage in the remaining electrodes is measured. In a computerized model, the voltage in the computational cells is calculated by solving the forward problem of the governing equation with known current source and known geometry [26]. It was previously used in a computerized head model [27] for correlation between skull thickness asymmetry and scalp potentials [28], for correlation between visual evoked potentials asymmetry and FIM measurements in stroke patients [5,6] and for monitoring cerebral artery stenosis [17]. The EIS method is a similar technique to the EBI, except for using a multi frequency current source. It has been shown to be a potential monitoring modality for patients with intracranial hemorrhage and stroke [20–22]. The EIT is an imaging technique that provides information about the spatial distribution of electrical conductivity within the human body. This method involves solving both the forward and the inverse problems of the governing equations in the volume conductor [24].

Published reports have demonstrated that a stroke lesion is usually located in one cerebral hemisphere [29]. No significant difference in impedance exists between the two symmetrical cerebral

* Corresponding author at: Biomedical Engineering Department, Faculty of Engineering, Tel-Aviv University, Tel-Aviv, 69978, Israel. Tel.: +972 3 6407397; fax: +972 3 6405312.
E-mail address: abboud@post.tau.ac.il (S. Abboud).

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hemispheres of normal humans, but stroke significantly increases the difference [18–20]. This can be utilized to determine which craniocerebral hemisphere (CCH) is with the lesion. Effective measurements of left–right asymmetry of impedance to determine which CCH was damaged by unilateral stroke lesion were previously studied [21].

In the present study, the feasibility of EBI technique for monitoring brain damage was analyzed using simulations on a realistic 3D numerical model of the head. Left–right asymmetry of the surface electrical potentials was calculated for several conductivities and volumes of the damaged region. The results were compared with the left–right asymmetry found in a head model with normal brain.

2. Methods

2.1. Solving Poisson's equation numerically

The quasi-static approximation was applied, in which the coupling between the electric and magnetic fields was neglected as well as tissue capacitive and inductive effects. The resulting Poisson's equation was numerically solved using the finite volume method (FVM) [26,27,30]. The FVM uses the integral form of Poisson's equation, as shown in Eq. (1).

$$\iint_{\partial V} (\sigma \nabla \emptyset)\, d\vec{s} = -\iiint_{V} I_v\, dv \tag{1}$$

where V [m^3] is the volume, σ [$\Omega^{-1}\,m^{-1}$] is the tissue conductivity, $\emptyset$ [V] is the electric potentials, $d\vec{s}$ [m^2] is an area unit vector normal to the volume conductor boundary, and I_v [A/m^3] is the volumetric injected current density, which is non-zero only at the injection positions. The body volume was divided into volumetric cells, and Eq. (1) was applied to each volume cell.

Applying the FVM approximation yields a large set of linear equations. This sparse set was solved iteratively using the successive over relaxation (SOR) method. Details of the formulation and the solution of the electrical potential equation with the FVM can be found in our earlier publications [17,26–28].

2.2. Numerical simulations on a realistic model of the head

2.2.1. The numerical phantom

The realistic numerical model of the head was created by Aubert-Broche et al., and published in 2006 [31]. This phantom is derived from different scans made upon a specific normal subject, and would be referred to as "the normal phantom". A homogenous cubic Cartesian coordinate system is used, each voxel representing a cubical volume of $1 \times 1 \times 1$ mm^3. This phantom was previously used in a similar modeling study [17], which investigated the feasibility of the bioimpedance technique for monitoring cerebral artery stenosis. Each voxel in the discrete version of the phantom is assigned with a tissue type from the following list: CSF (cerebro spinal fluids), grey matter, white matter, dura, fat, muscle, skin, skull, marrow and blood vessel. This segmentation was used to assign each voxel with the electric conductivity that characterizes its corresponding tissue at 50 kHz excitation [32–34], see Table 1.

The brain damage was modeled as a sphere in the left hemisphere, and different variations of the phantom were constructed according to the size and type of the damage (hemorrhage or thrombosis). In these models, voxels within the damaged region (sphere) were assigned with either plaque or blood conductivity. The volume of the damaged region ranged between 0.5 and 50 cm^3. Plaque conductivity was set as 0.07 S/m, which is one of the lower human aortic plaque conductivities found by Slager et al. [35], while blood conductivity was taken from Table 1. The head model was constructed with damaged regions in each of the following locations: front, middle and back of the left hemisphere.

Table 1
Typical conductivities of tissues in the human head at 50 kHz, taken from [32–34].

Tissue	Conductivity [S/m] at 50 kHz
Grey matter	0.128
White matter	0.078
Skull	0.021
CSF	2.000
Dura	0.502
Fat	0.024
Muscle	0.352
Skin (wet)	0.029
Marrow	0.003
Blood	0.701

2.2.2. The numerical simulations

The numerical solver was programmed in C and Matlab languages. Its accuracy was validated by running it on geometries with known analytical solutions, of a sphere with uniform conductivity and a sphere containing a current dipole source [36,37]. No significant differences were found between the results using the numerical solver and the analytical one. For all of those simulations, the SOR iterations converged after about 1000 iterations and the sum of the absolute errors over all voxels was in the order of 10^{-5} [V].

2.2.3. Potentials measurements and asymmetry calculation

Current injection was simulated by applying Neuman boundary condition of current sources at two selected voxels on the head surface. The injection electrodes were placed along the sagittal midline on the surface of the head. The first selected voxel was in the forehead and the other in the occiput. This imaginary line divides the head into two symmetrical parts, the right and left hemispheres as shown in Fig. 1.

Poisson's equation was solved, and measurements were taken at 16 surface voxels that correspond to the international 10–20 system, as shown in Fig. 1.

Left–right asymmetry was measured using the following normalized asymmetry index:

$$\mathrm{AI} = \frac{V_r - V_l}{V_r + V_l} \times 100\ [\%] \tag{2}$$

where V_r represents the potential measured with the right electrode, and V_l represents the potential measured with the corresponding left electrode. This asymmetry index corresponds to the EEG electrodes of the international 10–20 system (Fp1–Fp2, F7–F8, T3–T4, T5–T6, and O1–O2). For each damaged region configuration, the potential at each point was calculated with respect to a reference point Cz, according to Fig. 1. Fig. 2 graphically summarizes the simulations conducted. Increased injury severity was modeled as a larger damaged volume.

3. Results

Fig. 3(a)–(d) shows the asymmetry index (%) versus perturbation volume (cm^3) for the case of hemorrhage. Three different damage locations were simulated, central, frontal and occipital, and the asymmetry index was calculated for the anterior temporal (T3/T4), central (C3/C4), frontal polar (Fp1/Fp2), and occipital (O1/O2) positions, respectively. As can be seen, there is a native asymmetry in a normal brain [46]. Moreover, the asymmetry index increases as the damage volume increases.

Fig. 4(a) and (b) shows the asymmetry index (%) versus perturbation volume (cm^3) for the case of thrombosis. Two different damage locations are presented, frontal and occipital, and the asymmetry index was calculated for the frontal polar (Fp1/Fp2), and occipital (O1/O2) positions, respectively. As can be seen, unlike in hemorrhage, in the case of thrombosis damage the asymmetry index decreases as the damage volume increases.