NUMERICAL ANALYSIS OF INTRAMUSCULAR ELECTRIC FIELDS GENERATED BY SURFACE ELECTRODES ON LOWER LIMBS

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Abstract

A three-dimensional finite difference model of the thigh and two-dimensional finite elements model of shank have been designed. In the models inhomogeneities and anisotropies of fat, skeletal muscles and bones were considered. The proposed methods have used for solving the problem of electrical field penetration in the tissue due to bipolar low direct current stimulation with surface electrodes. The electrical field strengths into target neuromuscular structures have been analyzed. In particular, the work is intended to provide theoretical support for clinical applications concerning FES of denervated muscles or influence of the electric field on nerve regeneration and wounds healing.

Introduction

Electrical and electromagnetic field directly and indirectly influence on biological structures in the tissue. Indirect effects are essential basis for method of geometrically selective electrical stimulation of nerve and muscle cells through action potentials. Biomechanical outcomes of indirect stimulation are muscle contraction, sensation etc. Direct effects of electrical and electromagnetical stimulation of neuromuscular system are also found when steady or pulsating electrical currents are applied to the affected system. Recent studies have shown that magnetical stimulation may affect bone fracture healing when pulsating magnetic flux in range of 0.1 to 3 mT is applied /10,14,18/. Relatively low current density in range of 30 to 110 $\mu A/cm^{2}$ may affects healing of wounds and skin ulcers /3,5/. Recent reports have described the possible influence of electrical field strength 0.15 V/m limb regeneration due to the application small DC currents /2,14/ . The reported data about magnetic flux densities, electrical field strengths and current densities and other parameters of stimuli which may have influence on biological systems are not described precisely and consistently. The comparisons of parameters are not satisfactory occurrent /16/. The reasons lies in variety of geometry and anisotrophic and inhomogenious properties of the volume conductor /17/.

The measurements of field characteristics are in most cases problematical specially in humans. The measuring methods may disturb the applied field when low densities are used. The additional possibility is two or three-dimensional modeling of different biological tissue structures taking in to account the variety of geometrical and substantial properties in reasonable extension of details. There are known the reports which have shown the methods for field calculation on surface of body when sources are inside the body. The great deal of idealization have been proposed in order to simplified the model in level of analytically solvable cylindrical or spherical problem /9,11,12,16/. These studies have same relevance mostly for electrophysiology. In cases when external sources are applied directly on the surface of body or inside with implantable systems the geometrical shapes of electrodes and tissue inhomogenity and anisotrophy play essential rule for field penetration and distribution. The maximum idealizations are not allowed /4,8,13,15/. The numerical determination of the field distribution into the stimulated **biological** structures is therefore relevant for design and positioning of surface as well as implantable electrodes in order **to** improve the selectivity and controllability of motor responses; for design of stimulators and for study of possible mechanisms of direct effects of the stimulation. In this study the numerical calculations of steady potential fields in models of lower extremities are described. The results of calculation are compared with data which are reported in references as efficient **for nerve regeneration.**

Method

There are four different class of methods for potential determination in the volume conductor: Analytical, integral equation, finite elements and finite difference methods. Analytical methods are not applicable because the process of idealization toward cylindric or spheric geometry generate unrealistic model. Integral equations methods are suitable only for relatively low number of inhomogenities. Finite elements method has been used for calculation of isopotential field in below knee section of limb. Finite difference method is used for determination of electrical field in three dimensional model of the above knee part of lower extremity. Also finite difference model has been created for potential field determination near ulcer in sacral region of the back.

Plonsey /11/ was advised that problem of electrical field penetration in living substance can be solved quasi statically. Using this suppose, the current density satisfies the equation

$$\nabla . J = i \qquad (1)$$

Where ∇ is the del operator, J is the current density (Am^{-2}) and i is the current source density (Am^{-3}). The current density J is related to the electric field E (V/m) by Ohms low in differential form.

$$J = \gamma E \qquad (2)$$

where γ is the specific conductivity tensor (S/m). In case of orthogonal coordinate system all nondiagonal elements are zero. However, the specific conductivities along coordinate axes are different in skeletal muscles. Electric field E is related to the electric potential V by

$$E = -\nabla V \qquad (3)$$

If conductivity tensor γ is referred to the principal axes of Caretsian coordinate system then it is determined by γx, γy, γz. Combining (1), (2) and (3) gives

$$\nabla \cdot J = -\frac{\partial}{\partial x}\left(\gamma_x \frac{\partial V}{\partial x}\right) - \frac{\partial}{\partial y}\left(\gamma_y \frac{\partial V}{\partial y}\right) - \frac{\partial}{\partial z}\left(\gamma_z \frac{\partial V}{\partial z}\right) \qquad (4)$$

The equation (4) can be solved in a number of ways. We developed our own Pascal program code for finite difference method solution of the problem. The advantages of the program is relatively easy for entering the various geometrical shapes anisothropies, inhomogenities and boundary conditions which have been included in the model. The useful and efficient computer graphic presentation of the results has been also enabled into the large program package. The disadvantage of the program code is time consuming numeric algorithm for large set - up to 60.000 of difference equations to be iteratively solve on IBM PC computer.

Using the large-scale finite elements method on Cray-II S computer the model for the analysis of field in two-dimensional feasibility study has been developed. The major advantage of PAFEC 75 package on this computer is fast basic processing . Bat entering the data is more time consuming and also postprocessing, graphics and interpretations are less practical.

Above knee limb model design

The electrical field penetration in the tissue near lesion of n. ischiadicus has been calculated. Positive surface electrode is positioned beneath glutaeus maximus and the negative electrode is positioned beneath distal part of muscle vastus lateralis. The position of sciadic nerve lesion is not known precisely, but her pathway is 1 to 2 cm on the flexor site of femur. The model has been designed from anatomic atlas /1/. Four inhomogenities have been considered in the model: interface between electrodes and skin, fat tissue, skeletal muscle and bones. The conductivities are known from relevant references /5,6/. The conductivity of skeletal muscle is 0.4 S/m in longitudinal and 0.1 S/m in both transversal direction. The fat has conductivity 0.05 S/m in all directions. the bone has conductivity 0.001 S/m and skin 0.0025 S/m in longitudinal and 0.005 S/m in both transversal directions. Discretization has been performed in resolution of 1 cm and potential field is calculated in 38416 points and because of nearly cylindrical geometry of the thigh the potential field was considered in 21700 points. Estimated position of lesion of the sciatic nerve is at point (x=17, y=10, z=10) cm.

Below knee limb model design

In addition a lower limb finite elements model has been developed and has been numerically processed. This model is intended to provide theoretical base for clinical programmes concerning denervated muscle stimulation. Namely, the excitation and contraction of the antagonistic pair of muscles i.e. plantar flexors is directly depended on field distribution in lower limb. This contraction diminishing desired dorsiflexion if denervated and therefore weak pretibial muscle group is stimulated in order to correct the gait pattern of patients with lower motor neuron lesion. In this initial stage of the study a two-dimensional finite elements model of thickness 1 mm has been designed. Finite elements mesh has been fitted on anatomic picture of the shank.

Results

The isopotential lines in steps of 10 mV are plotted for sections x=17 cm, y=10 cm, z=10 cm on Figures 1., 2. and 3. respectively where the position of the sciatic nerve lesion has been estimated. The field was initiated by bipolar stimulation of the + 10 V. The calculation of strength of electrical field, vector E and current density was enabled from equations 2 and 3. In the /14/ was proposed that the field strength suitable for peripheral nerve regeneration is 0.15 V/m. This particular data are based on small animal experiment. At present authors have not available references about clinical relevant range of electrical parameters which effects the peripheral nerve regeneration in humans. In our experiment the numerical value of electrical field strengths are Ex=0.25 V/m, Ey=0.5 V/m and Ez=0.02 V/m which are comparable with the data mentioned above. Considered DC voltage in range from ±10 to ±60 V, is usual applying as an input on par of electrodes in other clinical applications. The general validation of the model design has been realized by measurement of whole resistivity between electrodes by four points U-I method. The difference between calculated and measured resistiveness was in range of 50 to 100 % which is acceptable while both the resistivity and calculation are dependant primarily on skin electrode contact, but the shapes of isopotential lines are more sensitive on correct design of limb model. The proposed integral criterion is known as an efficient tool for validation of the models.

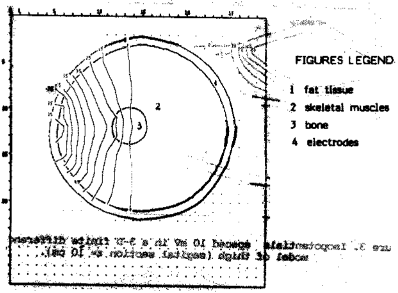

Figure 1. Isopotentials spaced 10 mV in a 3-D finite difference model of thigh (transversal section x= 17 cm).

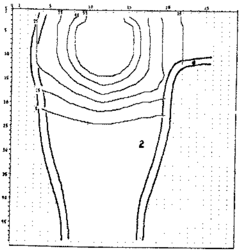

Figure 2. Isopotentials spaced 10 mV in a 3-D finite difference model of thigh (lateral section y= 10 cm).

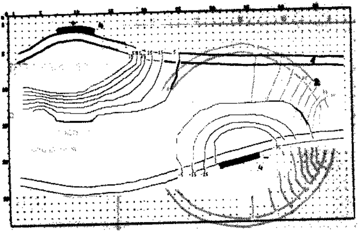

Figure 3. Isopotentials spaced 10 mV in a 3-D finite difference model of thigh (sagital section z= 10 cm).

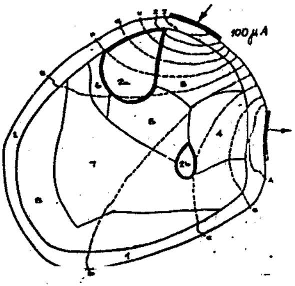

Figure 4. Isopotential spaced 840 mV in a 2-D finite elements leg model of thickness 1mm.

Result from an preliminary two-dimensional study of model is shown in Figure 4. The isopotential lines shows that field strength is the largest in muscle tibialis anterior assigned with number 3. The regions 2 and 2a represents the tibia and fibula respectively. The model design need to be improve with additional sections and with more realistic surface electrode placement and various configurations.

Conclusion

The potential field penetration in limb due to external generator was determined. The major part of electric potential is distributed between electrode and skin surface and also on layer of fat tissue under electrode placement. The electrical field in the tissue is highly nonhomogeneous and the range of the electrical field strength E (V/m) at the location of the sciatic nerve lesion is comparable with the data reported in available references. Position and shape analysis of the electrodes based on several criteria. The first step of the analysis is occurrent calculation of the field. The second step is an application of the achieved results using appropriate criteria. Unfortunately, problem of the criteria determination is not fully solved yet. There are present alternatives, which is reasonable and relevant characteristic parameter for estimation of the desired influence of electrically generated stimuli on the neuromuscular system: potential distribution, field strength or related current density, or force on polarized structures into muscles and nerves given by equation (5) or perhaps some combination ?

$$F = \nabla (p.E) \qquad (5)$$

Where p (As m) is a dipol momentum and E (V/m) is electrical field strength.

In order to improve the proposed methods advanced computer graphic presentation and fast numerical calculation must be achieve. We expecting that following this way extended sensitivity study on two or three-dimensional models will be enable.

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