Sensitivity Distribution Simulations of Electrode Configurations for Monitoring Tissue Grafts

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Abstract— **Monitoring of the tissue graft during and after the grafting operation is useful in reducing the risk for tissue ischemia, which may lead to even graft loss. Possible complications should be detected as early as possible in order to minimize the re-operation. Three models representing muscle tissue were created in FEMLAB: an isotropic model and two anisotropic models, the latter ones having the electrodes either perpendicular or parallel to the muscle fibres. Eleven tetrapolar measurement configurations having varying inter-electrode distances were modelled in each model to study their measurement sensitivity distributions. The results showed effects of anisotropy on both the measured impedance and the associated sensitivity distributions. For example, regions of negative sensitivity or depth for maximum sensitivity were dependant on whether the electrodes were placed perpendicular or parallel to the muscle fibres. The results point out also how to estimate the tissue anisotropy and how to measure impedance changes deeper in the tissue volume. The impedance method seems to be suitable for monitoring the muscle graft healing. However, more work is needed for reliable interpretations between the measured impedance and physiological changes.**

Keywords— **Anisotropy, bioimpedance, FEM, sensitivity distribution, tissue graft.**

I. Introduction

Tissue grafting is a surgical operation that is used to fill tissue defects with similar tissue from another part of the body. Reason for grafting arises either from congenital tissue lack, an accident, an infection, arterial disease, diabetes or from tumour ablation [1]. After joining the graft into the new site its function must be followed to make sure the proper healing. Sufficient perfusion is the main contributor in that. Grafts are often placed under the skin or deep in the body which evokes challenges for the monitoring.

Graft monitoring suffers from the lack of basic devices while it is done mainly by clinical assessments such as by detecting temperature, testing capillary circulation, checking up tissue oxygenation transcranially or directly if target lies at easy site [2]. The clinical assessments measure however only the symptoms of already weakened blood circulation. If the weakening is not detected early enough it may lead to tissue ischemia, which might cause necrosis and graft loss.

Technological methods have been under interest since the 1980's [3]. Nowadays blood flow monitoring devices like Doppler ultrasound and flow meter are used. The graft temperature can be monitored with surface probes and the oxygenation by a transcutaneous monitor. The technical monitoring devices are usually used after joining the graft at the defect site and used approximately for 72 hours.

Bioimpedance methods generally have several advantages including low costs, versatility, simplicity and non-invasiveness. On the other hand, reliability often remains an issue, especially when the basics of the signal origin are not widely understood. Bioimpedance has been proposed for graft viability and rejection monitoring [4].

This study was conducted to gain basic knowledge in properties of various tetrapolar electrode configurations aimed at measuring muscle tissue graft function. Measurement sensitivity distributions were simulated in isotropic and anisotropic models and the most suitable configurations for various measurement purposes were investigated.

II. Materials and Methods

A. Sensitivity distribution by lead fields

Sensitivity distribution of an impedance measurement gives a relation between the impedance Z (and change in it) caused by a given conductivity distribution (and its change). It describes how effectively each region is contributing to the measured impedance signal. If conductivity change is not involved, the impedance is obtained with

$$Z = \int_v \frac{1}{\sigma} \bar{J}_{LE} \cdot \bar{J}_{LI} \; dv \qquad (1)$$

where $\bar{J}_{LE}$ and $\bar{J}_{LI}$ are the current density fields (i.e. impedance lead fields) associated with the current and voltage leads [5]. This equation gives the contribution from each volume to the total Z, and the dot product of the two fields expresses the sensitivity to conductivity changes throughout the volume conductor. As the scalar field may possess positive and negative values depending on the orientation of the two lead fields, the measured impedance may increase,

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decrease or be entirely unaffected in consequence of a conductivity change in a particular region.

In modelling, the current density is contributed to the volume of the examined element itself. Therefore it is simpler to operate with electric fields which can be considered as point values. Knowing that J = σE, the Eq. (1) becomes

$$Z = \int_v \sigma \, \overline{E}_{LE} \cdot \overline{E}_{LI} \quad dv \qquad (2)$$

where $\overline{E}_{LE}$ and $\overline{E}_{LI}$ are the lead fields expressed as electric fields.

B. Models and simulations

Bioimpedance signal has many contributors and is therefore challenging to be modelled exactly. For our purposes, however, a simple model may well be used to derive basic information on the form of sensitivity distributions. Finite element models were constructed and solved with FEMLAB® 3.1 (Comsol AB, Stockholm, Sweden) in 3-D quasistatic DC mode without taking into account the polarization phenomena or tissues frequency dependence.

Volume conductors: The muscle tissue or the volume conductor was modelled with a simple box of 255 x 100 x 100 mm^3. Altogether three models were created, each having a total of 63 259 elements. The anisotropy was studied in two ways, when the electrodes were perpendicular to the muscle fibres (model AVCX) and when the electrodes were parallel to muscle fibres (model AVCY). The longitudinal conductivity was 0.6 S/m and the transversal conductivities 0.09 S/m. Additionally, isotropic model (IVC) with conductivity of 0.6 S/m was constructed.

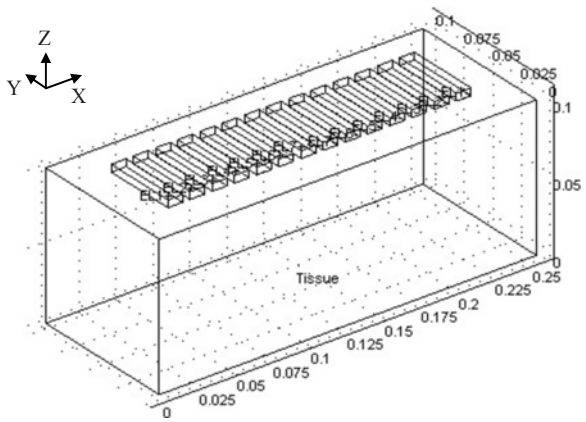

Fig. 1 The electrode grid on top of the volume conductor

Electrodes: The electrode geometry was rectangular with the size of 10 x 50 mm^2 and thickness of 5 mm. Altogether 14 electrodes were modelled on top of each volume conductor but only one pair was used at the time so that the associated lead fields could be simulated. The volume conductor geometry and the whole set of electrodes are presented in Fig. 1.

C. Simulations and analysis

Simulations: Seven electrode pairs were formed for each model and associated lead fields were simulated by applying a unit reciprocal current through each electrode pair. Figure 2 shows the pairs having the widest and narrowest distance between each other on a 2D view.

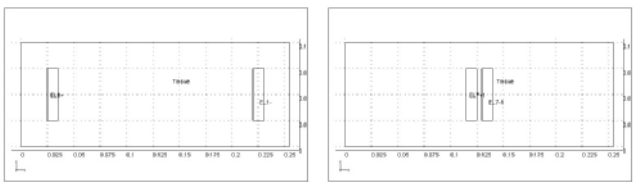

Fig. 2 Example electrode pairs. On the left the pair with widest distance between each other (pair1), on the right the narrowest distance (pair7).

The conjugate gradient solver with symmetric successive over-relaxation preconditioner was chosen for simulations. After solving the electric fields, 160.000 values were extracted for further analysis in a 100 x 40 x 40 grid.

Electrode combinations: With the lead fields of the seven electrode pairs different combinations were derived to study tetrapolar measurement systems. Systems were formed in two ways: Case A - having a stable current feeding electrode location but varying the voltage sensing pair farther from the current feeding pair. This system had an increasing inter electrode separation, IES. Case B – both electrode pairs were moving towards the model centre, keeping the distance between the current and voltage electrodes constant (constant IES). Both of the sets included 6 different tetrapolar systems: A1-A6 and B1-B6. The ordinary number of the electrode system describes also the voltage electrode separation: 1 equals the widest spacing and 6 the narrowest spacing. Table 1 contains information on which electrode pairs are used in each case.

Table 1 Electrode pairs of each tetrapolar measurement combination

System	#1	#2	#3	#4	#5	#6
Case A	Pairs 1&2	Pairs 1&3	Pairs 1&4	Pairs 1&5	Pairs 1&6	Pairs 1&7
Case B	Pairs 1&2	Pairs 2&3	Pairs 3&4	Pairs 4&5	Pairs 5&6	Pairs 6&7

Analysis: The sensitivity values were calculated for each grid point according to the Eq. 2. The lead fields and sensitivity distributions were analysed in several ways:

- 3D visualization: Three dimensional figures of the measurement sensitivity distributions. The aim was to investigate the locations of positive and negative sensitivity regions.
- Sensitivity integrals: In order to study how the magnitudes were changing as the electrode system varies, the integrated sensitivities were calculated along the three orthogonal axes. The integrals were calculated e.g. for each x axis point so that the current point x was substituted into the equation and the corresponding y and z values were integrated. As a result an x-directional sensitivity integral matrix (slice by slice) was achieved. The y and z directional sensitivity integrals were solved in the similar way.
- Depths of maximum sensitivity: The peak values were extracted from the sensitivity integrals with respect to the z-axis (depth from the electrode surface).
- Half-sensitivity volume: This refers to the volume which creates half of the total sensitivity.
- Negative sensitivity proportions: The amount of the grid points with negative sensitivity was counted and compared against all the grid points (100 x 40 x 40).
- Target sensitivity: Three target regions (surface, middle and deep) were chosen and their total sensitivity was compared with the whole sensitivity.

III. Results

A large number of analyses were conducted for the lead field data. Individual lead fields for the three models with the 7th electrode pair are visualized in Fig. 3, manifesting the effect of anisotropy. Sensitivity to detect target region on the surface and deeper in the medium as a function of electrode combination is shown in Fig. 4.

On the basis of various analysis methods applied (detailed results not shown here), optimal measurements for different cases may be suggested:

Getting the highest signal magnitudes: Electrode orientation parallel to the muscle fibres. A small inter electrode spacing between the current and voltage electrodes and wide voltage electrode spacing (modelled system A1).

Getting the deepest maximum sensitivity: Electrode orientation parallel to the muscle fibres. A large inter electrode spacing and the voltage electrode separation as narrow as possible (modelled system A6).

Getting the steadiest measurement sensitivity: Electrodes parallel to the muscle fibres. A medium inter electrode spacing (modelled system A3-A5).

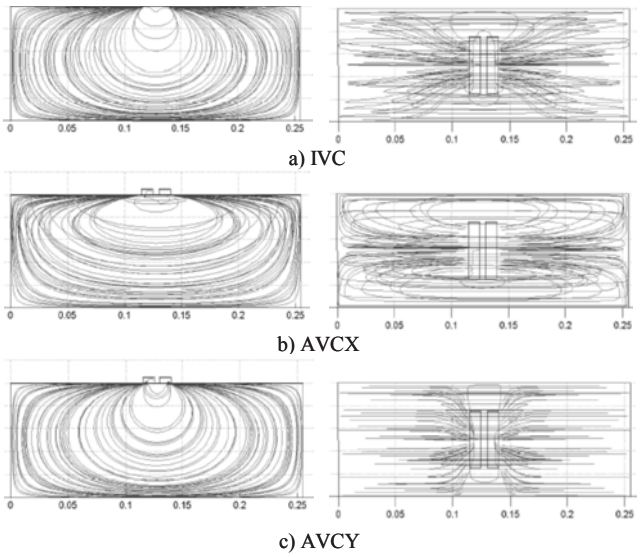

Fig. 3 Current density flow lines with the 7th electrode pair. LEFT: x-z view, RIGHT: y-x view

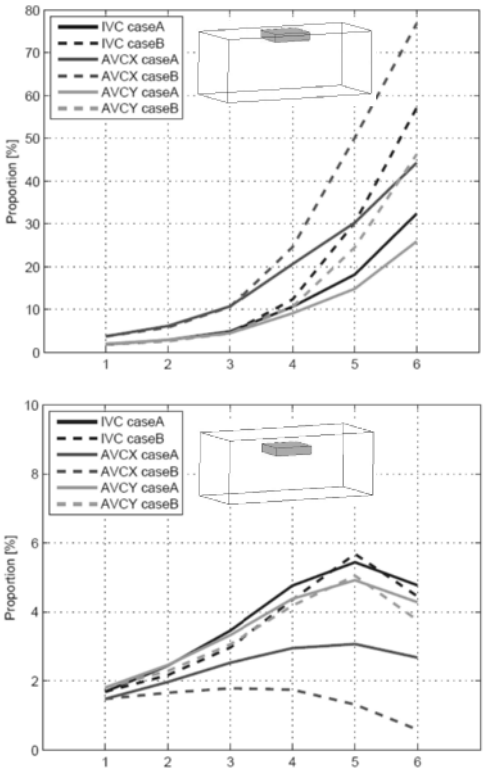

Fig. 4 Target sensitivity proportions of the whole sensitivities. Red cube is the target volume. X-axes corresponds to voltage electrode separation (1 = widest, 6 = narrowest). IVC = isotropic model, AVCX = anisotropic, electrodes perpendicular to the muscle fibers, AVCY = anisotropic, electrodes parallel to the fibers. Case A = fixed current electrodes, increasing IES. Case B = electrodes moving closer to the centre, constant IES.

Detecting possible anisotropy: Measurements with the same electrode system in both orientations (electrodes perpendicular and parallel to the muscle fibres).

Detecting deep impedance changes: Simultaneous measurements with the same tetrapolar system (A5), electrodes both perpendicular and parallel to the muscle fibres. The difference of the signals is the impedance change originating from the deeper sources.

IV. Discussion

Tetrapolar systems have been used previously in studies concerning graft monitoring such as impedance plethysmography of a subcutaneous free flap transfer [6] and the tissue oedema monitor with multiple frequencies [7]. Contrary to the present study, electrode settings are rarely analyzed specifically, suggesting the systems used are not optimal. Studying the sensitivity distributions could be utilised in developing more efficient bioimpedance measurements.

Several methods were developed and applied in analysing the sensitivity distributions associated with tetrapolar impedance measurements. The modelling results showed clear effects of anisotropy on the impedance values. The most effective way is to place the electrodes parallel to muscle tissue because it leads on to the highest signal magnitudes and results in the sensitivity distributions that are similar to the isotropic tissue. Thus, the parallel placement ensures that the measurement frequency can be increased without markedly disturbing the sensitivity distributions. The modelling results also pointed out means to detect the tissue anisotropy and, more interestingly, indicated how to measure the impedance changes originating in deeper parts of the tissue.

As this was a first attempt towards developing a graft monitor, the model geometry was simply a rectangular box with electrodes on top of it. The model consisted only of the muscle tissue with the fibres oriented solely along the orthogonal axes, neglecting the complexity of biological tissue anatomy and physiology. Missing model parameters will evidently affect the fields and finally the measured impedance values.

V. Conclusions

There's a need for an efficient tissue graft viability monitor that could be used preferably with many types of grafts. The bioimpedance method has several advantages which makes the method versatile in contrast to other methods.

When designing a bioimpedance tissue graft monitor, several factors must be considered. According to the earlier studies the blood flow and tissue condition can be detected by measuring the bioimpedance but interpreting the signal origin requires careful planning and studying the contributors of the measurement.

The reported method requires still development before the impedance values can be used for screening the graft function. The results of this study, however, can be used when improving the sensitivity of the bioimpedance measurements. By this way the impedance measurements of the anisotropic tissue can be optimized instead of using the conventional tetrapolar systems with the equidistance electrode placement. The study gives basis for the future work when developing a monitor for detecting the properties and the function of a tissue graft.

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