Visualizing transplanted muscle flaps using minimally invasive multi-electrode bioimpedance spectroscopy

R Gordon, V Zorkova, M Min, I Rätsep
Department of Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
E-mail: rauno@elin.ttu.ee

Abstract. We describe here an imaging system that uses bioimpedance spectroscopy with multi-electrode array to indicate the state of muscle flap regions under the array. The system is able to differentiate between different health states in the tissue and give early information about the location and size of ischemic sub-regions. The array will be 4*8 electrodes with the spacing of 5mm between the electrodes (the number of electrodes and the spacing may vary). The electrodes are minimally invasive short stainless steel needles, that penetrate 0.3 mm into the tissue with the goal of achieving a wet electric contact. We combine 32 configurations of 4-electrode multi-frequency impedance measurements to derive a health-state map for the transplanted flap. The imaging method is tested on a model consisting of 2 tissues and FEM software (Finite Element Method –COMSOL Multiphysics based) is used to conduct the measurements virtually. Dedicated multichannel bioimpedance measurement equipment has already been developed and tested, that cover the frequency range from 100 Hz to 1 MHz.

1. Introduction
Transplanting tissue for reconstructing damaged areas or filling tissue defects is a common surgical practice. During the transplantation, a tissue graft is harvested from patients own body (special donor-areas [1]) and joined to the required site. Medical staff can externally assess if the operation was successful and occasionally monitor the healing process, but a more reliable system is needed for continuous monitoring of the healing process of the transplanted tissue flap for getting earlier signal if surgical repair is needed. Bioimpedance measurement provides a cheap and handy method for continuous monitoring of such transplants. Measuring bioimpedance has been proposed as a diagnostic method in various medical conditions, but post-operation monitoring of transplanted tissue grafts is easily one of its' most promising medical applications. The visualization method proposed in this work is limited to tissue grafts placed on the body surface.

2. Proposed diagnostic system
We propose a bioimpedance-spectroscopy based system for easy visualization of the health state of a transplanted muscle flap. We use minimally invasive electrode array in 4*8 configuration for acquiring an image of health-state regions under the array. The electrodes are 0.3 mm long needles with thickness up to 0.1 mm. They are spaced 5 mm apart in the regular grid array to form a patch that covers a 15*35 mm area. The electrode array should be flexible and it would be installed on the operation site so that all needles penetrate a little into the tissue to gain a wet electric contact.
The measurement system will perform 4-electrode impedance measurements between all the 32 electrodes with 32 different configurations. The whole set of measurements should be performed under a minute or 10 minutes because the tissue health state is not very rapidly changing. The frequency range is selected to be from 100 Hz to 1 MHz for reliable tissue health characterization. Two measurement devices have been built and tested in our electronics laboratory with the capabilities to perform these measurements with the needed accuracy [2, 3]. The measurement system gathers the frequency characteristics of all 32 configurations and passes the data to the imaging system.

The imaging system determines the state of tissue under each electrode configuration based on the measurement results. It then composes an image, where tissue health areas are clearly visible, for a doctor to further analysis. The image can easily be sent to the doctor’s cell-phone by an MMS for example.

3. Locally assessing the tissue health state
Each frequency characteristic of a 4-electrode impedance measurement is compared to a set of existing characteristics (healthy, ischemic, necrosis, other/error) with their lower and upper tolerances. The impedance data for muscle tissue has been acquired from Gabriel et.al. [4]. The data for other essential types has been gathered [5, 6, 7], but not yet composed for this system, because it is inconclusive for our needs. To test our working system, we used 2 distinct tissues - muscle and fat - with their full frequency characteristics. The 4-electrode measurement simulation results of those tissues are shown in Figure 1 with lower and upper tolerances used in a sample system testing.

If the measurement result from one 4-electrode configuration is set within the bounds of healthy muscle, then it will be indicated with value 1 on the final image. If the result accounts as clearly ischemic, then the respective area will be marked with value 2. If other distinguishable states can be identified, other values will be used to mark them.

![Figure 1](image)

**Figure 1.** Impedance frequency characteristics of 4-electrode measurement simulation with muscle and fat tissue.

4. Testing the precision of simulations
The bioimpedance measurement was simulated at different FEM-mesh densities to determine, if the mesh resolution is good enough for accurate results. The 4-electrode measurement was simulated with the domain (a muscle flap 100*40*10 mm with 32 electrodes) consisting of 182,000 tetrahedral mesh elements and 360,000 tetrahedral mesh elements.

The results of this test show that there is negligible difference between high-resolution mesh and lower-resolution mesh (less than 0.1 %) in all sections of the frequency characteristic. Therefore the lower resolution mesh was used for all the simulated measurements.
5. Positioning the measurement results
The 4-electrode impedance measurement has positive sensitivity areas (impedance increase locally in that area contributes to signal rise) as well as negative sensitivity areas (impedance increase contributes to signal fall). The sensitivity of a 4-electrode impedance measurement can be calculated as a dot product of 2 electric fields: the lead-field from electrodes 1-4 and the lead-field from electrodes 2-3. The lead-fields of 1-4 and 2-3 were calculated in a 80*80*20 grid and then the dot product of the 2 fields was found in each of the 3D grid points. The sensitivity maps for 4-electrode measurements were calculated with two cases: electrodes in a straight-line (used in 28 measurements, Figure 2) and electrodes in corner formation (used in 4 measurements, Figure 3). The 3D sensitivity maps were used to determine the areas in the image, where the diagnosis of the specific 4-electrode measurement was applied. The diagnosis is one of the following: healthy, ischemic, necrosis or error and in the final image it is being marked with colour codes 1,2,3 or 4 (refer to section 3).

Figure 2. The 4-electrode impedance measurement with linearly positioned electrodes. Sensitivity maps of 3 top layers and the positioning of diagnostic patch (12-pixel patch) on the right.

Figure 3. The 4-electrode impedance measurement with corner formation electrodes. Sensitivity maps of 3 top layers (of 20) and the positioning of diagnostic patch (9-pixel patch) on the right.

6. Composing the image
The final image will be composed from all the patches that are acquired from the 32 measurement configurations. The patches can have values 1 (healthy), 2 (ischemic) or other. There will be 28 shape-1 patches (Figure 2, right) to show results of all the linear electrode configurations, and 4 shape-2 patches (Figure 3, right) to fill the corners of the image that would otherwise be left empty. When the patches are positioned on the image, there will be overlaps. The overlapping pixels are taken as average values of patch pixels. When all patches are on the image, the distracting holes between the patches will be filled in with average values of neighbouring pixel values.

7. Results
To test the system, we ran all measurements in a computer as simulations with Comsol Multiphysics software. The object under test was described as 10*4*1 cm block composing of 2 tissues (Figure 4). On that biological object the electrode array was placed. In the modelling domain only the tips of the electrodes are specified, that penetrate into the tissue.

When the measurements are performed on the model, the imaging system effectively composes an image from the patches. The resulting image composition is shown in Figure 5 with 3 steps: 1) the
composing of the image with measurements from 28 linear electrode configurations; 2) the corner patches have been added to the image; 3) the holes are filled with average values of neighbours. The two tissue areas are accurately distinguished.

Figure 4. The 3D modelling domain, composed of 2 tissues and the array of 32 electrodes. Electric field from 2 corner-electrodes is shown on the model surface with colour.

Figure 5. The 3 steps of image composition. The tissues are distinguished with colours 1 and 2.

8. Discussion
The number of electrodes can be increased and the distance between electrodes can be chosen some other value, when physical experiments and clinical trials suggest a need for other configurations. Same applies also for the length and thickness of the needles, which depends on the tissue type that will be targeted with this diagnostic system.

9. Acknowledgements
This research was supported by the European Union through the European Regional Development Fund.

References
[1] Microsurgeon internet site, http://www.microsurgeon.org/
[2] Min M, Parve T, Ronk A, Annus P and Paavle T 2007 Synchronous Sampling and Demodulation in an Instrument for Multifrequency Bioimpedance Measurement IEEE Transactions on Instrumentation and Measurement 56 (4) 1365-72
[3] Annus P, Kuusik A, Land R, Haldre E, Min M, Parve T and Poola G 2007 An energy efficient wearable tissue monitor IFMBE Proc. 17 ICEBI 2007 13th Int. Conf. on Electrical Bioimpedance and 8th Conf. on Electrical Impedance Tomography 2007 Graz, Austria, 240-3
[4] Gabriel S, Lau R W and Gabriel C 1996 The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz Phys. Med. Biol. 41 2251-69
[5] Dean D A, Ramanathan T, Machado D and Sundararajan R 2007 Electrical impedance spectroscopy study of biological tissues Science Direct
[6] Ristic B, Kun S and Peura R A 1996 Muscle Tissue Ischemia Monitoring Using Impedance Spectroscopy: Preliminary Results IEEEExplore
[7] Schaefer M, Gross W, Ackemann J and Gebhard M M 2002 The complex dielectric spectrum of heart tissue during ischemia Science Direct