From impedance theory to needle electrode guidance in tissue

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Abstract. Fast access to blood vessels or other tissues/organs can be crucial in clinical or acute medical treatment. We have developed a method for needle guidance for use in different types of applications. The feasibility of an automatic application for fast access to blood vessels during acute cardiac arrest, based on this method, has been evaluated. Suited electrode setups were found by development of needle electrode models used in simulation and sensitivity analyses. In vitro measurements were done both to determine the fundamental properties of the electrodes for use in the models and to confirm the simulation results. Development of algorithms for tissue characterization and differentiation was based on in vivo impedance measurement in porcine models and confirmed in human tissue in vivo. Feasibility was proven by application prototyping and impedance data presented as invasive Electrical Impedance Tomography (iEIT). Our conclusion is that this method can be utilized in a wide range of clinical applications.

1. Introduction
As participators in an ongoing resuscitation project we wanted to explore the feasibility of using bioimpedance measurements to confirm intravascular needle position. For administration of drugs and liquid for induced hypothermia fast access to blood vessels was required. Earlier we have presented a method for guiding of needle electrodes based on bioimpedance measurements [1]. Further development of the method and gathering of fundamental properties of different needles [2] and electrode systems has now been done. The aim was to determine if our method could be utilized as part of an application for fast vascular access, but also to refine the method in general for use in other types of clinical applications. Different needles and electrode systems was used in measurements in-vitro and in in-vivo porcine models. Impedance spectra for different types of tissues were measured and compared to earlier results [3,4].

2. Methods
Suited needle electrodes were found after a market survey and testing of available needles. Different special designs of electrodes were also evaluated, but not carried further since commercial available stainless steel electrodes with acceptable properties were found. In-vitro testing of electrodes was done to determine electrode properties with focus on spatial sensitivity, stability over time, and influence from Electrode Polarization Impedance (EPI) [5]. Monopolar measurements were obtained by using 3-electrode setups [6] or 2-electrode setups with a very large counter electrode [5]. Pilot studies gave no significant difference between the two as we used them. Stability of electrode properties over time were determined by impedance measurements as function of time and exposure to saline and
excitation currents [2]. Repeatability was also tested in-vivo by repeated measurement over time in porcine models.

The spatial sensitivity was tested by measurement at different insertion depths in a saline tank [1], and in a piece of bacon from the local grocery store. The bacon was used to obtain a more realistic in-vitro model. By use of a servomotor we measured the impedance at 10 kHz as function of time at constant insertion speed. The insertion depth could then be calculated from the time and speed. To illustrate the sensitivity we plotted the measured impedance modulus on a picture of the bacon in the plane of insertion.

A theoretical evaluation of the sensitivity was also done by development of a Finite Element (FE) model of the needle setup. Plotting the equipotential line where the potential had dropped to 3 % of the simulated excitation potential was done to determine the 97 % sensitivity zone.

A laptop/DAQ-card prototype was constructed for in-vivo testing of the tissue discrimination method. The results were used to construct an array of needles for insertion towards the femoral artery. Impedance spectra were taken for all needles at different depths (a step length of 3 mm was obtained by insertion of Plexiglas spacers) to obtain a matrix of measurement points covering a sufficient cross section of a volume where the femoral artery was expected to be found. Ultra sound images were taken to aim the array and to be used as a gold standard for verification of the results.

3. Results and discussion

All needles were dominated by EPI at frequencies up to some kHz, where the tissue or saline properties gradually were more dominant as the frequency was increased [1]. The differences in magnitude of the EPI and the stability due to saline exposure were large between the tested needle types [2]. The 97 % sensitivity zone was found to be inside a radius of about 2.6 mm in the saline tank measurements. In the bacon measurements abrupt changes in the impedance modulus were seen when the needle entered from one tissue type to the next (figure 1).

![Figure 1. Measured modulus at 10 kHz plotted as function of insertion depth in bacon. The mark at about 2 kΩ indicates the starting point of the horizontal needle insertion path.](image)

The results from the FE-analysis are illustrated in figure 2. The 97 % equipotential line (surface in 3D) was found in a radius of 3.7 mm from the needle tip. This result was not exactly the same as obtained in the in-vitro experiment, thus further refinement of the models are planned for a follow-up study. However, the results gave an estimate of the sensitivity zone that was sufficient for use in the design of our needle array. By using 3 mm distance between the needles the conductance of the needles did not interfere significant on the neighbour needle, and still blind volumes between the needles could be avoided. The in-vivo measurements on the porcine model gave impedance spectra [1] in accordance with results from earlier investigators [3,4]. Sufficient tissue characteristic data was obtained in the impedance spectra from the array measurement to localize femoral vessels. This result was illustrated by plotting the phase angle at 316 kHz for each pixel in a matrix (described in more detail in a paper under preparation). We look upon this plot as a first approach to construct an invasive Electrical
Impedance Tomograph (iEIT). The feasibility for separating muscle and fat by a method based on needle electrode impedance measurement was showed [1]. Separation of other tissue types may also be possible, but even if we only can discriminate blood, muscle and fat, the method most likely can produce valuable needle guidance for many clinical procedures as surgery or drug administration.

![Figure 2](image)

**Figure 2:** Result form the FE-simulation. The white zone illustrates the volume responsible for 97% of the measured impedance in a homogeneous medium.

4. Conclusions
The experiences from this project gives reason to believe that further a development of the impedance based method can enable needle guidance in a wide range of clinical applications.

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