Finite element model of needle electrode sensitivity

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Abstract. We used the Finite Element (FE) Method to estimate the sensitivity of a needle electrode for bioimpedance measurement. This current conducting needle with insulated shaft was inserted in a saline solution and current was measured at the neutral electrode. FE model resistance and reactance were calculated and successfully compared with measurements on a laboratory model. The sensitivity field was described graphically based on these FE simulations.

1. Introduction
The main objective for this work was to describe the sensitivity field of a needle electrode with an insulated shaft. The description of sensitivity field for this type of electrode is important in the ongoing project [1] describing a new method for anatomical needle positioning in the clinic.

As shown below, the sensitivity field $S$ can be expressed by the following [2]:

$$S = \frac{1}{|J_{rec}|}$$

($J_{rec}$ is the reciprocal current density vector and $J_{cc}$ the needle current density vector.) Since this is a two electrode system, $S$ becomes:

$$S = |J|^2 \quad [1/m^4]$$

To obtain the necessary information in order to express the sensitivity field of a needle electrode system, a Finite Element (FE) model was used. This FE-model was physically based on an actual lab-model with a needle in saline solution used by Kalvøy et al. [1].

The needle was modeled (in the FE application) with an insulated shaft and had electrode polarization impedance (EPI) incorporated based upon measurements on the lab-model. A literature study showed that a description of the EPI as a layer with a certain thickness, permittivity and conductivity was not easily obtained. Martinsen & Grimnes [2] stated that EPI thickness could be expected to be from 1 to 10 nm depending on the concentration of the electrolyte solution.

2. Methods
To establish a FE-model able to simulate the properties of the laboratory needle electrode setup, we first had to determine the main properties of the real setup used in the laboratory. The FE-application Comsol Multiphysics (CM) was used to establish and solve this FE-model.

The real setup consisted of three main parts: active electrode surface (Double layer/polarization impedance and of course the metallic part of the needle), needle insulation and the saline solution.
Because of the low system frequency, we chose to treat the bulk saline in the tank as a pure resistance [3].

When the non-insulated active electrode surface is brought into contact with biological tissue or an electrolytic solution, electrochemical phenomena will occur and can be observed as electrode polarisation impedance (EPI).

The main challenge in modelling EPI was the small dimensions of geometry. Grimnes & Martinsen describe [2] that layer thickness approximately equals the Debye-length, meaning that small dimensions which will give an unnecessary complicated FE-model. To get a functional FE-model we had to set the FE EPI-layer as a thicker layer, but with electrical properties corresponding to the actual EPI-layer. This resulted in a FE-model with a layer thickness of 0.5 μm with an adapted conductivity/permittivity giving the correct values for the conductance/susceptance. The electrical properties of the EPI-layer were given by the measurements on the LAB-model.

The saline solution was modelled as a cylinder with height 35 mm and radius of 52.5 mm. Anything between this cylindrical boundary and the needle was defined as saline (conductivity σ = 1.3 S/m [2]).

We defined the needle insulation as a cylindrical capacitor with the Teflon insulation as the dielectric. The capacitance will then depend on the insertion depth according to the area of insulation exposed to the saline solution.

The needle “Disposable Monopolar Needle Electrode, 37 x 0.33 mm, Medtronic Inc, Minneapolis, US” had an active electrode area of 0.3 mm². The thickness of this insulation was estimated to 26 μm based on information from the manufacturer.

![Figure 1 The needle (37 X 0.33 mm)](1)

![Figure 2 The needle electrode geometrical model](2)
Figure 3 The complete model. The needle tip is marked with a square. The contents of this square can be seen in the next figure.

Figure 4 A magnified section of the mesh from the proximity of the needle. Due to the small dimensions the 0.5 µm EPI layer cannot be seen on this figure.

The two previous figures show the axis-symmetric FE-model. This model is a 2D-model until the set of valid equations are to be solved. CM then revolves the model 360 degrees and the solution becomes a 3D-solution.

A series of FE-simulations were made by reducing the distance between the needle tip and the bottom of the saline tank. Model impedances were recorded and compared with the measurements on the LAB-model from Kalvøy & al [1].

Figure 5 Comparison of FE-model and Lab model. $Z'$ and $Z''$. FE-model to the left.
3. Results and Discussion

The recorded current density vectors and potentials from the FE-simulations compared well with the measurements on the LAB-model. Calculation of the sensitivity zone was done by plotting the potential distribution. This showed that the sensitivity zone for this needle electrode in saline solution had a spherical shaped sensitivity zone with a radius of approx 3.75 mm. This figure is in accordance with the observations from the LAB-model measurements when the needle either approaches the bottom of the saline tank or the surface of the saline solution.

![Figure 6](image)

**Figure 6** "97 %-zone" i.e. potentials and sensitivity field. This figure shows that the sensitivity field is a sphere with radius $r=3.75$ millimeters.

Some deviations between the FE-model and the LAB-model are observed and closely related to the necessary simplifications of needle electrode geometry in order to establish a well performing FE-model. The main reason is the simplifications of the EPI-thickness and adaption. This will be subject to further work.

4. Conclusion

It has been shown that sensitivity field in a measuring system involving a needle electrode can be modelled, solved and described with a Finite Element model. In this system sensitivity field has been estimated to be a spherically shaped zone with a radius of approximately 3.75 mm from needle metal surface. This result complied with the measurements on the needle-lab-model.

References

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