Comparison of four different FIM configurations—a simulation study

F J Pettersen\textsuperscript{1,2}, H Ferdous\textsuperscript{2}, H Kalvøy\textsuperscript{1,2}, Ø G Martinsen\textsuperscript{1,2} and J O Høgetveit\textsuperscript{1,2}

\textsuperscript{1} Department of Clinical and Biomedical Engineering, Oslo University Hospital, Norway
\textsuperscript{2} Department of Physics, University of Oslo, Norway

E-mail: fred.johan.pettersen@ous-hf.no

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Abstract

Focused impedance measurements (FIM) are used in several fields, and address the problem of measuring the volume impedance of an object within a volume conductor. Several electrode configurations are possible, and these have different properties. Sensitivity fields of four configurations have been investigated. We present one new development of an existing FIM configuration, and we made finite element models of the configurations to analyse and compare them both graphically and numerically. The models developed have a variable-sized mesh that allows us to build complex models that fit easily in computer memory. We found that one configuration in particular, FIM4, was superior to the others in most aspects. We also analysed the effects of very high sensitivities in and under the electrodes. We found that even if the sensitivity is very high under the electrodes, the effects of inhomogeneities were not as high as one might expect.

Keywords: focused impedance measurement, finite element model, simulation, three Rs

(Some figures may appear in colour only in the online journal)

1. Introduction

Electrical impedance in volume conductors is measured in many ways. For all but the simplest cases, it is difficult to know to what degree different sub-volumes in the conductor contribute to the measured result, i.e. the sensitivity field distribution. This means that in many volume impedance measurements, the understanding of the complete measurement problem is too low. An extension to this problem is the cases where we want to measure the impedance in a
specific volume with as uniform sensitivity in our target volume and as little influence from other volumes as possible.

Focused impedance measurement (FIM) using four, six, and eight electrodes has been presented in Rabbani et al. (1999) and Rabbani and Karal (2008). These methods are focusing the sensitivity to a region roughly shaped as a half-sphere below a flat surface.

The FIM techniques may be applied for a wide range of applications such as cancer diagnosis, bladder emptying, and lung ventilation (Rabbani and Kadir 2011). FIM can be useful since it enables us to target the measurement in tissues or organs of interest. In the study of measuring gastric emptying, FIM along with its 3D sensitivity was found effective (Rabbani et al. 1999). A linear relationship to change in expired volume of air was found in a previous study when implemented to a focused zone of the lung in a subject (Rabbani and Kadir 2011). In principle, the dielectric properties of lung tissue varies greatly as a result of air ventilation, between expiration and inspiration (Nopp et al. 1993), which ultimately offers an area of opportunity to implement electrical impedance measurement systems for further study with FIM (Kadir et al. 2010). One such pilot study showed that to have a thorax mapping in terms of transfer impedance an appropriate model is required before FIM technique is implemented (Ferdous et al. 2013). One of the appealing properties of the technique is that it is possible to make simple and low-cost equipment based on FIM. A FIM based instrument is typically based on a low-end microcontroller and a handful of analogue components. This is in contrast to more advanced systems like EIT, x-ray, MRI, and ultrasound. Since the equipment is low-cost, it is especially suited for use in poor countries.

Brown et al., and Islam et al. have addressed the problem of analysing the sensitivity field distribution using Matlab simulations based on Geselowitz’ lead field theory (Geselowitz 1971). These analyses were done for points in a mesh with 1mm distance in the x, y, and z-directions. The models consisted of 343 000 and 8000 000 points, respectively. The models can be used to calculate sensitivity in each point. Our approach is also based on the Geselowitz theory, but we realize it in COMSOL Multiphysics (MPH) finite element models (FEM) that gives us some extra possibilities such as a variable mesh that can be made finer, i.e. the distance between nodes is smallest around small geometrical objects, around regions of special interest. For instance, in our models the highly interesting electrodes are made as 372 tetrahedra instead of only a point in the previous work. In addition to this, the Matlab models only gave sensitivity while our models have current density vectors and potentials available for all points. Expressions for sensitivity (equation (5)) and volume impedance density (equation (6)) are added to enable us to graphically display sensitivities and to enable us to calculate transfer impedance. The previous work is limited to semi-infinite homogenous volumes while the presented FEM models do not have this limitation. In addition, the FEM model allows us to model almost any geometrical shape. The larger feature-set of the FEM-tool enables us to extract more interesting information out of the model. Furthermore, we present some new metrics that should be taken into account when evaluating a given measurement configuration.

The software models were used to analyse the different FIM set-ups in silico. Using the models described in the paper we are able to measure with the different electrode configurations and determine how they are influencing the measurement results. The sensitivity field distribution can be crucial when measuring in biological tissue or other sample of non-homogenous nature.

Different configurations of electrodes have been used to measure impedance. FIM is a special set-up for impedance measurement where two or four electrodes are current carrying (CC), and two or four electrodes are used for voltage pick-up (PU). Some configurations have two steps where the electrode usage is changed. In these cases, the configuration requires
Figure 1. Top view of electrode configurations. Dimensions are not to scale. (a) FIM4, (b) FIM6, (c) FIM8a, (d) FIM8b.

simple post-processing. The benefit of FIM is that simple circuitry allows us to measure in the region of interest (Rabbani et al 1999).

However, one of the major problems of such impedance studies is that unless real life experiments have been executed it is difficult to avail information beforehand, which is obviously time-consuming and challenging to rectify if necessary. To solve these problems, the experiments can be done in silico using FEM software for modelling. Another benefit of in silico experiments is replacement of animal experiments in accordance with the three Rs of animal welfare (Russel and Burch 1959).

We are presenting a new tool for selecting the optimal electrode configuration for a given FIM problem. Examples of such problems are the thoracic mapping where the use of a FEM-tool could aid in choosing the best FIM configuration, and to improve understanding of the measurement results.

2. Method

2.1. Model descriptions

All models are 50 cm wide × 50 cm long × 25 cm high. The height is set to half the width since previous work (Brown et al 2000, Islam et al 2010) have shown that sensitivity is decreasing rapidly when moving away from the electrode plane. The electrodes are placed on top of the models. Electrode radius is varied according to column 2 in table 4. The electrode height is equal to electrode radius. In addition to the electrode itself, a half-sphere is made under the electrode. The half-sphere has the same electrical properties as the bulk material, and is used to (a) force the FEM tool to make the mesh finer in these regions, and (b) to define a region for volume integration. The radius of this half-sphere is varied from the same radius as the electrode and up to 10 mm in 2 mm steps. The inner electrodes for all models form a square with 4 cm sides. For FIM6, FIM8a, and FIM8b, the CC electrodes form a square with 12 cm sides. Configurations are shown in figure 1. A sphere is placed just underneath the surface for the same reasons as for the half-spheres. The sphere has the same electrical properties as the bulk material. The sphere radius is 1/3 of the spacing between the inner electrodes, i.e. 1.33 cm, and is touching the top surface of the model. The works presented in Brown et al (2000) and Islam et al (2010) suggest that this is a depth where sensitivity might be high.

To simulate the effect of an inhomogeneous material under an electrode, two ellipsoids were placed under one CC-electrode in the FIM8a-model. One ellipsoid was placed in the region with positive sensitivity, and the other in the region with negative sensitivity. The regions of positive and negative sensitivity were determined in the previous simulations. The ellipsoid has radius identical to the radius of the electrode in x-direction, and y-direction, and radius identical to half the electrode radius in the z-direction, which is shown in figure 2.
Figure 2. Placement of ellipsoids beneath one electrode. The one marked A is in the region of negative sensitivity, while the one marked B is in the region of positive sensitivity.

Figure 3. Surface mesh illustrating variable mesh structure.

The meshes were generated with settings that gave approximately 75 000 tetrahedral elements.

Figure 3 shows how the mesh is getting finer around the region of interest (the electrodes). For simplicity, only the surface meshes are shown.

The materials properties are shown in table 1.

The current flows from the electrode designated by the first letter through the model to the electrode designated by the second letter. Letters, where the first letter identifies the positive terminal and the second letter identifies the negative terminal, also identifies voltage pick-up electrodes.

For all set-ups, we are may say that we are making several measurements of the same quantity. In an ideal setting, each measurement would give the same value, and a summation of two measurement results would give the double of the real value, so to get the real value, we
Table 1. Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (sigma) (S m⁻¹)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>1</td>
<td>The bulk of the model</td>
</tr>
<tr>
<td>Electrode</td>
<td>100</td>
<td>Electrode material</td>
</tr>
<tr>
<td>Low conductivity</td>
<td>0.01</td>
<td>Inhomogeneity below electrode</td>
</tr>
<tr>
<td>High conductivity</td>
<td>100</td>
<td>Inhomogeneity below electrode</td>
</tr>
</tbody>
</table>

would have to calculate the average of the two values. Here, we follow the same logic; we do several transfer impedance measurements and take the average. In particular, what we do is to calculate the sensitivities for the different measurements and then average these. These calculations are all done within MPH. This method is in contrast to the work by Islam et al where results were added together (Islam et al 2010). Adding the results would enable comparison, but it would not let us use the result when calculating expected transfer impedance as we also do. The validity of our method has been verified by comparing FIM-simulations to phantom measurements (Abir et al 2013). Since all set-ups give different results, we may also argue that all measurements should be normalized, but we did not do this since we wanted to estimate final impedance.

2.1.1. FIM4. Four electrodes in a square. As described in Rabbani and Karal (2008). Electrode placement is as shown in figure 1(a).

The procedure:

1. Measure transfer impedance using AC as CC, and BD as PU.
2. Measure transfer impedance using AB as CC, and CD as PU.
3. Calculate the average Z (transfer impedance).

2.1.2. FIM6. Six electrodes as described in (Rabbani et al 1999). Two independent current sources AB and AC. One PU, pq. Electrode placement is as shown in figure 1(b).

2.1.3. FIM8a. This is a set-up where two 4-electrode measurements are done, and the results averaged. For each of the two 4-electrode set-ups, the electrodes are placed in a row. The two set-ups are 90° on each other. Electrode placement is as shown in figure 1(c).

The procedure:

1. Measure transfer impedance using AB as CC, and pq as PU.
2. Measure transfer impedance using CD as CC, and rs as PU.
3. Calculate the average Z (transfer impedance).

2.1.4. FIM8b. FIM 8b is an evolvement of FIM6 and FIM8a. Two sets of independent CC-electrodes 90° on each other. Two sets of PU-electrodes rotated 45°. Current is delivered simultaneously in the two CC-pairs, and PU is done in two rounds. Electrode placement is as shown in figure 1(d).

The procedure:

1. Measure transfer impedance using AC and CD as CC simultaneously, and pq as PU.
2. Measure transfer impedance using AC and DC as CC simultaneously, and rs as PU.
3. Calculate the average Z (transfer impedance).
2.1.5. Simulation set-up. Simulations are done in COMSOL MPH version 4.3. A set of partial differential equations is needed to define how the FEM-tool are doing its calculations. In the cases where an appropriate pre-defined equation set is not defined, the generic equations (1) through (4) can be used. For the case of COMSOL MPH, there exist arrange of pre-defined equation sets that models several physical systems such as heat flow, electric currents, magnetic fields, acoustics, fluid flow, etc. For our models, we have used a predefined set called Electric Currents physics interface (COMSOL 2013) which contains the equations (1) through (4).

The interior of the materials are handled by
\[ \nabla \cdot J = Q_j \]  
(1)

\[ J = (\sigma + j\omega\varepsilon_0\varepsilon_r)E + J_e \]  
(2)

\[ E = -\nabla V \]  
(3)

and the external boundaries by
\[ n \cdot J = 0. \]  
(4)

The simulations are done for DC only, which means that \( \omega = 0 \) in equation (2). The symbols in equations (1) through (4) means:
- \( \nabla \cdot \) is the divergence of a vector field.
- \( J \) is electric current density.
- \( E \) is electric field intensity.
- \( Q_j \) is electric charge.
- \( \sigma \) is electric conductance.
- \( j \) is the imaginary unit.
- \( \omega \) is frequency in radians per second.
- \( \varepsilon_0 \) and \( \varepsilon_r \) are vacuum permittivity and relative permittivity, respectively.
- \( J_e \) is external current density.
- \( \nabla V \) is the gradient of the potential.

For a complete explanation please see the MPH reference manual (COMSOL 2013). For further information on FEM for electromagnetic problems, there are excellent text books available (Humphries 1997).

2.2. Extracted numbers

Several numbers are extracted from the model simulations.

2.2.1. Fractions. The negative fraction (NF) tells us how much volumes with negative sensitivity contribute to the measured transfer impedance. This is a number between 0 and 1, and should ideally be 0. The next number is called sphere fraction (SF) and tells us how much the sphere just below the model surface contributes to the measured impedance. SF is a number between 0 and 1 for a configuration with NF = 0 and should ideally be 1 if we want to focus our measurement on the sphere. If the NF is non-zero, the number might be higher than 1.

To calculate NF and SF, we first define volume impedance density \( z \) for each point in the model. This is simply sensitivity multiplied by the resistivity as shown in (6). Sensitivity is given in equation (5). If we integrate \( z \) for all points in the volume, we end up with the transfer impedance. If we integrate over a smaller volume, \( V_{\text{SUB}} \), then the contribution from
Table 2. Sensitivity variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRMAX</td>
<td>$\frac{\text{max}</td>
</tr>
<tr>
<td>SRSPHERE</td>
<td>$\frac{S_{\text{AVERAGE}}}{S_{\text{SPHERE}}}$ Ratio between average $S$ for the sphere and average $S$ for the whole model. Electrodes are not included.</td>
</tr>
</tbody>
</table>

$V_{\text{SUB}}$ to the total transfer impedance is the result. MPH has mechanisms to allow us to select such smaller volumes based on geometry or any available numerical property of a given point. This functionality allows us to investigate regions of special interest

$$S = \frac{\vec{J}_{\text{CC}} - \vec{J}_{\text{PU}}}{I_{\text{CC}} I_{\text{PU}}} \left[ \frac{1}{m^4} \right]$$

(5)

$$z = \rho S \left[ \frac{\Omega}{m^3} \right]$$

(6)

where

$\rho$ is the resistivity of the material.

$S$ is sensitivity.

$\vec{J}_{\text{CC}}$ is the current density originating from simulation where current is sent into the model through the CC electrodes.

$\vec{J}_{\text{PU}}$ is the current density originating from simulation where current is sent into the model through the PU electrodes, i.e. the reciprocal current.

$I_{\text{CC}}$ is the measurement current used in the model.

$I_{\text{PU}}$ is the reciprocal measurement current used in the model.

Both $I_{\text{CC}}$ and $I_{\text{PU}}$ is set to 1A to simplify calculations. Then the NF is calculated using

$$NF = \frac{\iiint z_{\text{NEG}} \, dV}{\iiint z \, dV}$$

(7)

where

$$z_{\text{NEG}} = \begin{cases} 
  z & \text{if } z \leq 0 \\
  0 & \text{if } z > 0
\end{cases}$$

(8)

And SF is calculated using

$$SF = \frac{\iiint_{\text{SPHERE}} z \, dV}{\iiint z \, dV}$$

(9)

2.2.2. Depth of negative sensitivity. To quantify how deep the region where $S$ is negative is, the parameter negative sensitivity depth is defined as

$$\text{NSD} = \frac{\text{Depth of negative } S}{\text{Distance between inner electrodes}}$$

(10)

and was found by probing an isosurface plot of $S = 0$.

2.2.3. Sensitivity ratios. Two ratios of sensitivities are defined in table 2. SRMAX defines how large the sensitivity ratios are. A very high number indicates regions with high sensitivity that could potentially cause problems. The SRSPHERE say how high the sensitivity is in the sphere where we want sensitivity to be high is. A high number means that the focus on the sphere is high.
Table 3. Impedance contribution definitions.

<table>
<thead>
<tr>
<th>Variable definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{EL-ABCD} = \iiint_{ELECTRODES \ ABCD} z \ dV[\Omega]$</td>
<td>Contribution from electrodes A, B, C and D to final measured impedance</td>
</tr>
<tr>
<td>$Z_{HSP-ABCD} = \iiint_{HALFSHERES \ ABCD} z \ dV[\Omega]$</td>
<td>Contribution from half-sphere below electrodes A, B, C and D to final measured impedance</td>
</tr>
<tr>
<td>$Z_{EL-pqr[s]} = \iiint_{ELECTRODES \ ABCD} z \ dV[\Omega]$</td>
<td>Contribution from electrodes p, q, r and s to final measured impedance</td>
</tr>
<tr>
<td>$Z_{HSP-pqr[s]} = \iiint_{HALFSHERES \ ABCD} z \ dV[\Omega]$</td>
<td>Contribution from half-sphere below electrodes p, q, r and s to final measured impedance</td>
</tr>
</tbody>
</table>

2.2.4. Contribution from electrode regions. The fine simulation mesh in the electrode regions allowed us to have a closer look at the contribution to final impedance form these regions. Four electrode related contributions are defined in table 3.

2.2.5. Inhomogeneities. An extra set of simulations was done to the FIM8 a-model to investigate the effect of inhomogeneities in the region below the electrodes. A base simulation was done with no inhomogeneities, and a number of combinations of low and high conductivities in the two regions were simulated. The percentage change in total averaged transfer impedance impedance was found.

3. Results

3.1. Sensitivity plots

Sensitivity plots from the simulations are given in figures 4–8.

3.1.1. Comparison of configurations. Figures 4 through 7 show plots of sensitivity for the different configurations. There are four plots for each configuration. Plot (a) shows the interface between the zone of negative and positive sensitivity. The plot is created by plotting a sensitivity isosurface with $S = 0$. For (b), (c) and (d) in all figures the plot range is from $-150000 \ [m^{-4}]$ (dark blue) to $150000 \ [m^{-4}]$ (dark red) via $0$ (light grey), with the exception of the FIM4-plots (figure 4) where the range is $\pm 350000 \ [m^{-4}]$ due to lower and higher sensitivities. For plot (b), the inner rings in the electrodes are the electrode dimensions, while the outer ring is the half-sphere below the electrodes. The plots show the sensitivity in three different planes:

1. One plane parallel to the electrode plane (figure n b)). This plane cuts the sphere in the middle, i.e. 1.33 cm below the surface.
2. One vertical plane that is parallel with one of the sides of the model (figure n c)).
3. One vertical plane that is rotated 45° (figure n d)).

To ease comparison, the viewpoint is the same for all models. The electrode radius is 4 mm for all plots.

3.1.2. Sensitivities in presence of inhomogeneities. The plots in figure 8 shows how the sensitivity changes in presence of inhomogeneities under an electrode.
Figure 4. Shape of negative sensitivity region, and sensitivities for three different planes for FIM4.

3.2. Numbers

Tables 4 and 5 show the extracted number for all configurations.

The contributions to the average transfer impedances of the electrodes and the half-spheres under the electrodes are presented in table 5.

Percentage change of impedance due to inhomogeneities is presented in table 5 and figure 8.

4. Discussion

4.1. Model limitations and strengths.

By using a variable size mesh instead of the fixed-size mesh used by Brown et al and Islam et al we introduced a method to reduce the numerical problem, and thus made it easier to
keep the entire model in the computer memory. This may not be an issue for relatively small models, but by using variable-size grid, we may be able to analyse larger models than we were if we used fixed-grid models. Here, the term large model also means a model with high spatial resolution since it would require a large amount of grid points. It also means that it is possible to model geometries that are small compared to the complete model accurately. The Matlab method uses arguably less resources than a FEM-tool if the mesh was similarly sized and if we limit the model to only deal with a semi-infinite homogenous model.

For more complex models, and if we choose to extend the model to include frequency dependent properties, the variable mesh may make it difficult to find a numerical solution, and we may have to give up some of the dynamics in mesh size, and is by that falling back towards a mesh with points with fixed distance.

The model in the work presented here is for DC only since simulations in the frequency domain is identical but with numbers replaced with complex numbers. For models describing
real-world geometries such as body organs with much more complex tissue properties like presented by Gabriel and Gabriel (1996) a frequency simulation would be appropriate. An example of such a model is given by Pettersen and Høgetveit (2011).

The number-crunching capabilities of Matlab are impressive. But Matlab has no infrastructure to let users create a simulation model. This effectively limits the complexity of Matlab models to very simple models similar to the ones presented by Brown et al (2000) and Islam et al (2010). MPH and other FEM-tools have an infrastructure that is geared towards complex models and powerful post-processing.

A half-sphere with the flat surface on the model surface would probably have given better SF for all models, but was not used since one goal of developing a FIM-method is to locate materials with different electrical impedance below the surface, and a submerged sphere is therefore more realistic. Examples may be a cancer tumour below the skin surface and measurement of the electric impedance of a specific organ.
The configurations investigated here are only a small sub-set of all possible configurations. Which configuration to use depends on several factors like allowed complexity, focus requirements, and ability to detect a particular feature in the measurand.

The electrodes are modelled as cylinders that have a conductivity that is 100 times higher than the bulk material. The electrodes are set up to either carry no current or to carry a given current. In the case of no current, the electrodes are simply geometries with higher conductivity than the surroundings. In the other case, the top surfaces of the electrodes are defined to be a surface where a given current of 1 [A] is flowing. Since we are using an ideal dc current source, we do not have to consider interface effects such as polarization or contact impedance. We could do simulations with higher detail levels, and by that be able to see effects of interfaces. The given set of equations (1) through (4) will not be able to model all effects that are caused by the ionic nature of electrical bioimpedance and the interfaces between domains with electronic and ionic charge carriers. The simulations of inhomogeneities beneath one electrode will to

Figure 7. Shape of negative sensitivity region, and sensitivities for three different planes for FIM8b.
Figure 8. Effect of inhomogeneities illustrated by plotting sensitivity. The plots represent different configurations of conductivity in the regions of negative and positive sensitivity (a) low–low, (b) low–high, (c) high–low, (d) high–high.

Table 4. Numerical results from simulations. El. radius is electrode radius, and the variables NF, SF, SRMAX and SRSPHERE are defined previously.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>El. radius (mm)</th>
<th>NF</th>
<th>SF</th>
<th>SRMAX</th>
<th>SRSPHERE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIM4</td>
<td>2</td>
<td>0.213</td>
<td>0.262</td>
<td>536115</td>
<td>1651</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.208</td>
<td>0.260</td>
<td>272715</td>
<td>1641</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.196</td>
<td>0.257</td>
<td>104252</td>
<td>1617</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.172</td>
<td>0.248</td>
<td>69521</td>
<td>1565</td>
</tr>
<tr>
<td>FIM6</td>
<td>2</td>
<td>0.532</td>
<td>0.114</td>
<td>885596</td>
<td>717</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.532</td>
<td>0.114</td>
<td>448783</td>
<td>719</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.530</td>
<td>0.115</td>
<td>178640</td>
<td>726</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.527</td>
<td>0.118</td>
<td>126373</td>
<td>746</td>
</tr>
<tr>
<td>FIM8a</td>
<td>2</td>
<td>0.491</td>
<td>0.100</td>
<td>725337</td>
<td>627</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.491</td>
<td>0.100</td>
<td>279517</td>
<td>627</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.491</td>
<td>0.100</td>
<td>124070</td>
<td>632</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.527</td>
<td>0.102</td>
<td>79798</td>
<td>641</td>
</tr>
<tr>
<td>FIM8b</td>
<td>2</td>
<td>0.396</td>
<td>0.114</td>
<td>504024</td>
<td>717</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.396</td>
<td>0.113</td>
<td>235780</td>
<td>715</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.491</td>
<td>0.113</td>
<td>97120</td>
<td>713</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.527</td>
<td>0.113</td>
<td>65690</td>
<td>713</td>
</tr>
</tbody>
</table>

a small degree illustrate some effects of what happens if the electrodes are not perfect or perfectly attached to the rest of the measurand. Since the models are simplified, and we use no 2- or 3-electrode configurations, we considered that the simplifications did not change the
Table 5. The contributions to the total average transfer impedance from electrodes and spheres below the electrodes are given as percentage of measured average transfer impedance.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Variable</th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIM4</td>
<td>$Z_{EL-ABCD}$</td>
<td>−0.029</td>
<td>0.144</td>
<td>0.815</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-ABCD}$</td>
<td>0.053</td>
<td>0.816</td>
<td>2.049</td>
</tr>
<tr>
<td>FIM6</td>
<td>$Z_{EL-ABCD}$</td>
<td>−0.085</td>
<td>−0.022</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-ABCD}$</td>
<td>0.004</td>
<td>0.049</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>$Z_{EL-pq}$</td>
<td>−0.077</td>
<td>0.087</td>
<td>0.425</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-pq}$</td>
<td>0.033</td>
<td>0.335</td>
<td>0.793</td>
</tr>
<tr>
<td>FIM8a</td>
<td>$Z_{EL-ABCD}$</td>
<td>−0.128</td>
<td>−0.039</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-ABCD}$</td>
<td>0.006</td>
<td>0.049</td>
<td>0.159</td>
</tr>
<tr>
<td></td>
<td>$Z_{EL-pqrs}$</td>
<td>−0.035</td>
<td>0.326</td>
<td>1.302</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-pqrs}$</td>
<td>0.012</td>
<td>0.510</td>
<td>1.205</td>
</tr>
<tr>
<td>FIM8b</td>
<td>$Z_{EL-ABCD}$</td>
<td>−0.080</td>
<td>−0.022</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-ABCD}$</td>
<td>0.004</td>
<td>0.048</td>
<td>0.144</td>
</tr>
<tr>
<td></td>
<td>$Z_{EL-pqrs}$</td>
<td>−0.001</td>
<td>0.465</td>
<td>1.796</td>
</tr>
<tr>
<td></td>
<td>$Z_{HSP-pqrs}$</td>
<td>0.015</td>
<td>0.622</td>
<td>1.449</td>
</tr>
</tbody>
</table>

Table 6. Results of inhomogeneities under electrode.

<table>
<thead>
<tr>
<th>Conductivity–positive Region</th>
<th>Conductivity–negative Region</th>
<th>Measured impedance change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Reference</td>
</tr>
<tr>
<td>0.01</td>
<td>0.01</td>
<td>−0.30</td>
</tr>
<tr>
<td>0.01</td>
<td>100</td>
<td>−4.15</td>
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<tr>
<td>100</td>
<td>0.01</td>
<td>2.38</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>−1.14</td>
</tr>
</tbody>
</table>

results significantly. Details on error sources in tetrapolar impedance measurements can be found in Grimnes and Martinsen (2007), and should apply here with some modifications.

4.2. Sensitivity plots

There are clearly significant differences between the configurations. As expected the FIM4, FIM8a, and FIM8b have sensitivity fields that are symmetrical around the x- and y-axis, while FIM6 is clearly not symmetrical. It is interesting to see how high the sensitivities in and beneath the electrodes are. It may be naturally to assume that any inhomogeneity in these regions would affect measurements to a high degree, but the simulations with inhomogeneities (table 6) shows us that the effect is surprisingly small. This can be explained by seeing the electrode and the inhomogeneity as a different shaped electrode. Figure 8 shows how the sensitivity is changed if inhomogeneities are present. The plots show us that where the conductivity is low, the sensitivity is low too. This can be explained by seeing the electrode and the inhomogeneity as a different shaped electrode.

4.3. Numbers

The results in table 4 tells us that there are large differences in what the actual measured value consist of depending on which configuration we choose. If we consider only one electrode radius, 4 mm, looking at NF, we see that the negative fraction varies from 0.208 for FIM4 to
0.532 for FIM6. This means that the risk of errors caused by objects placed in a region with negative sensitivity is higher for FIM6 than for the other configurations.

The SF tells us that the contribution to the sphere is much highest for the FIM4 configuration. But even so, the SF is still only in the range 0.100–0.262. This means that even if we have relatively good focus in our focus region, 73.8%–90% of the contribution to the total transfer impedance is originating from outside the focus region. Which again indicate that the FIM configurations analysed here, and probably similar configurations too, may have a rather limited use.

The electrode size affects all numbers, but the sensitivity ratio numbers (SRMAX and SRSPHERE) are most affected. The smaller the electrodes are, the higher the sensitivity ratios are. This tells us that large electrodes might be better if not other factors dictates use of small electrodes. The SF and NF were relatively little affected by electrode size for all models except FIM4. FIM4 has best values for SF and NF, but if constant electrode size is important, then FIM4 might be a poor choice.

The results in table 5 tell us that the contributions from the electrodes and the regions just below the electrodes are small even if the local sensitivities are very high. Even if we put inhomogeneities in these regions, we see (table 6) that the effect is relatively small. The inhomogeneities were modelled as ellipsoids with conductivity that was either 100 times higher or lower than the conductivity of the surrounding material placed under the electrode as shown in figure 2. The small effects on overall result may be explained in several ways. We may say that where the resistivity of a region is increased, the current density will naturally decrease too as long as the current has an alternative way to flow (as it has here), and thus reduce sensitivity according to equation (5). Similarly, in the case where resistivity is decreased, the sensitivity will be increased due to higher current density. When looking at equation (6), we see that the regions contribution to measured impedance is not only given by sensitivity, but also by resistivity, and that is changing in the opposite direction, and thus trying to cancel out the effects of sensitivity change. Another way of seeing it is that the inhomogeneities are causing an effective change of electrode placement and shape in the 3D-volume. But since the changes were relatively small compared to the distances between the electrodes, the effects were small.

As mentioned above, inhomogeneities will alter sensitivity. To further illustrate this, we can consider the case where an object with reduced conductivity is placed within our desired sensitivity region. Two things will happen:

(a) A low conductivity object will cause currents to move around it and thus move the sensitivity region away. This will result in reduced transfer impedance according to equation (6).

(b) A low conductivity object has higher resistivity, and will therefore result in higher transfer impedance according to equation (6).

This means that we may see the problem form an entirely different angle. If conductivity in our focus region differ much from the surroundings, then we start measuring more or less of the surroundings.

5. Conclusion

The presented work has shown that MPH is a very useful FEM tool to investigate volume impedance measurement problems. This is especially true when we consider models where there are large rations between small and large objects and inhomogeneities. Simulations allow us to explore the electrode configuration space and visualize and quantize alternative configurations.
The simulations showed us that of the four configurations analysed here, the FIM4 configuration is superior in terms of SF and NF. The simulations also showed that the sensitivities in and beneath the electrodes were surprisingly high, but even so, the inhomogeneities beneath the electrodes did not affect the measurements as much as one might expect. Similarly, effects of objects within our focus region will not have as much influence as we might expect.

Acknowledgment

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