3D Sensitivity of 8-Electrode FIM through Experimental Study in a Phantom

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Abstract

Focused Impedance Method (FIM) is a relatively new technique developed in the Biomedical Physics Laboratory of Dhaka University which allows improved localization of a zone without much increase in the complexity of measurement. Three versions using 8, 6 and 4 electrodes respectively have been conceived and developed. FIM has potential for characterization of biological tissues at depths non-invasively placing electrodes on the skin surface at appropriate locations, leading to detection or diagnosis of diseases or disorders. The present work is an experimental study of the sensitivity of the 8-electrode FIM system at different depths and lateral positions inside a volume conductor with respect to the electrode-positions using a cubical phantom with saline. An object of different conductivity and of size smaller than-the electrode separation was placed inside the phantom at different positions to measure the change of FIM value, called sensitivity in this work. The study verified the focusing effect at the central zone where the sensitivity remained high and almost constant laterally for a certain depth, falling sharply outside. At shallow depths, the sensitivity showed enhanced peaks under the electrodes which however, decreased fast with depth. The sensitivity falls off sharply with depth becoming almost constant at greater depths but with greatly reduced value. The sensitivity at off axis positions from the centre also reduced outside the focused zone. Slightly negative zones of sensitivity were observed at lateral positions far from the center of the electrodes, but the values were negligible. This work will help standardize the application of 8-electrode FIM for determination of impedance of organs inside the human body.

Keywords: Electrical Impedance, focused impedance method (FIM), phantom, sensitivity.

1. INTRODUCTION

Electrical impedance measurement techniques have been in use for over a century for characterizing physiological tissues and attempts have been made for detection and diagnosis of diseases and disorders, although with limited success (Schwan 1957). With the possibility of being non-invasive, electrical impedance techniques are potentially low cost and simple. Electrical impedance, specifically, impedivity, is a characteristic property of any material, including biological ones (Pethig 1979). Different body tissues may have different electrical impedivity, which can again vary between health and disorder. Biological tissues exhibit two important passive electrical properties; electrical conductivity due to free charge carriers (ions etc.) and dielectric properties like relative permittivity due to bound charge densities.

The electrical impedivity is thus a representation of the distribution of relative electrical conductivity and permittivity and hence has the potential for detecting inhomogeneity inside the body. The main cause for the limited success mentioned above is that electrical current distribution is complex in a human body which again depends significantly on the outer shapes of the body and inhomogeneity of internal impedance distribution. Localization of a target organ therefore, was almost impossible, which is essential for detection or diagnosis of diseases or disorders.

In the basic non-invasive electrical impedance measurement, two electrodes are placed on the surface of an object (a volume conductor) and the impedance measurement is used to determine the gross electrical characteristics of the whole volume of that object, with enhanced contribution from regions under the electrodes and that in between the two electrodes. For the impedance measurement a known amount of alternating current is injected through the electrodes and the resulting electrical potential difference is measured. However, the contact impedances of the electrodes contribute as added quantities, and in most cases, these mask the target values relevant to the bulk region inside. This is because the contact impedances are usually much larger than the bulk impedances and it is very difficult to extract the latter from the total measured value.

To avoid this problem, TPIM (Tetra-polar or Four-electrode Impedance Measurement) method evolved towards the end of the nineteenth century. In a typical configuration four electrodes are arranged in a line. Current is injected through the two outer electrodes while the resulting potential difference is measured across the two inner ones giving a transfer impedance or admittance. It also gives some localisation, however, the zone of sensitivity is rather wide and a target organ cannot be separated from its neighbouring organs. In order to improve the localization of the target region inside the effective zone of impedance measurement, a new technique, known as the Focused Impedance Method (FIM) was conceived and developed at the Biomedical Physics Laboratory of the University of Dhaka (Rabbani et al 1999). In the basic method transfer impedances are obtained using two orthogonal and concentric TPIM configurations and then summing or averaging the two values. This gives an enhanced sensitivity at the central region compared to its surroundings. Therefore, in this basic technique, a total number of eight electrodes are required, four for introducing the two orthogonal currents (current electrodes) and remaining four for recording two voltages (potential electrodes).

A 6-electrode version of FIM was achieved placing two potential electrodes diagonally at the central region at the intersections of the aprropriate equipotential lines instead of the required four in the above description (Rabbani et al 1999). These two electrodes could monitor the potentials for both the orthogonal current drive configurations. In another 4-electrode version of FIM four electrodes are placed at the corners of a square region in which current is injected through two adjacent electrodes while the potential is recorded across the opposite pair. The measurement is then performed for an orthogonal configuration and the average of the two measurements is taken (Rabbani and Karal 2008a).

In electrical impedance measurements it is important to know where to put the electrodes on the boundary to get the maximum contribution of the target organ into the measured impedance. Organs at points with higher sensitivity contribute more than those at points with lower sensitivity. Understanding of the point-sensitivity is thus essential in order to achieve success in electrical impedance methods. Sensitivity of a tetrapolar impedance measurement at a point *p* can be defined as the scalar product of the sum of two vector current densities (the lead fields) for unit current injection between the two pairs of electrodes (Geselowitz 1971). According to the reciprocity theorem the voltage and current electrodes can be swapped giving the same measured value. This is at the basis of this sensitivity definition. For a semi-infinite homogeneous medium (Brown et al 2000) showed that the vector lead fields are determined by the vector paths from the electrode to a point where the sensitivity is to be determined and the method is described below.

For a homogeneous and semi-infinite medium with the electrodes placed at points *a, b, c* and *d,* let the vector current densities at a point *p* due to current injection at points *a* and *b* be denoted by $\vec{f}_{ap}$ and $\vec{f}_{bp}$ respectively. These are directed along the lines joining the electrodes to the point of interest *p*. The lead fields for current injected at electrode pairs *a*,*b* and *c*,*d* are given by $\vec{p}_{ab} = \vec{f}_{ap} + \vec{f}_{bp}$ and $\vec{p}_{cd} = \vec{f}_{cp} + \vec{f}_{dp}$ respectively. The sensitivity is then defined by

$$S = \vec{p}_{ab} \cdot \vec{p}_{cd}$$

To get the sensitivity of the FIM, the sensitivity for the two individual tetrapolar impedance measurements should be summed. Following this definition (Islam et al 2010) determined the point sensitivity of the 8-electrode, 6-electrode and 4-electrode FIM's for a homogeneous semi-infinite media analytically. However, their analysis should differ from the point sensitivity in a finite volume and also with the presence of inhomogeneity. Hence, experimental determination of sensitivity remains a requirement for potential application of FIM. For such empirical approaches sensitivity may be defined as the relative change in impedance when a small object is placed inside a volume with uniform but different conductivity, compared to the background impedance without the object. Therefore, detailed study on the lateral sensitivity is required at different depths compared to the electrode surface.

Sensitivity for 4-electrode FIM technique was determined by our extended group at Dhaka University in a 2D phantom (Rabbani and Karal 2008b) and for objects with different conductivities (Karal and Rabbani 2010). 3D-sensitivity of 6-electrode FIM was investigated for points only along a line perpendicular to the center point of the electrode arrangements (Iquebal and Rabbani 2010). However in practical applications, it becomes almost impossible to ensure that the target object is always kept on the center axis or around it. Due to movement of test subject, lack of precision in electrode placement and inexperience, internal target organs may deviate slightly from the intended position on the central axis. Furthermore, no experimental study has been done so far on the sensitivity measurement of basic 8-electrode system. The present study was therefore taken up to investigate the variation of 3D sensitivity inside a volume conductor at on and off-axis points using a small object in a phantom paving the way to more realistic application of 8-electrode FIM.

2. METHODS

It is convenient to use equipotential surfaces in visualising the overall effects of placing small target objects in a volume conductor that are subject to electrical impedance measurements, which has been done in the following description. In the basic 8-electrode FIM, impedance measurements from two mutually perpendicular and concentric TPIM's performed sequentially or simultaneously are added. The setup is shown in figure 1. For the vertical TPIM, current-injection electrodes are A and B while the potential difference is measured between the points p and q. This essentially represents the difference of potentials between the equipotential lines aa' and bb'. Similarly, for the horizontal TPIM, current-injection electrodes are C and D and the potential measuring electrodes are r and s. The measurement essentially represents the difference of potentials between the equipotential lines cc' and dd'. As is evident from the figure, the impedance of the almost square shaped doubly shaded region in the centre, in between the four equipotential lines, contribute more than the other regions around.

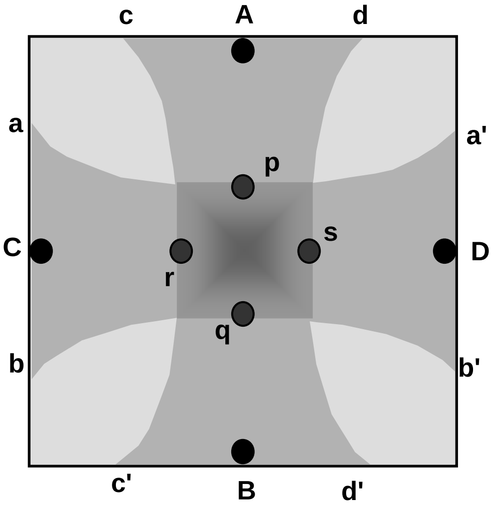

Fig. 1: Focused zone in 8-electrode FIM

To find the sensitivity of the FIM system experimentally, we placed a small object, preferably spherical, at different points inside the volume of a cubical saline phantom. In the experimental system the injected current amplitude is kept constant so that the measured voltage is proportional to the transfer impedance. Therefore, the impedance sensitivity can well be described in terms of the measured potential sensitivity. The potential measured with saline of uniform conductivity (without the object) is,

$$V_0 = V_{01} + V_{02},$$

where subscripts 1 and 2 refer to the two orthogonal TPIM values. Again that with a small object placed at position $\vec{r}$ is,

$$V(\vec{r}) = V_1 + V_2 .$$

Since the driven current amplitude is maintained essentially constant, the transfer impedance is directly proportional to the amplitude of the measured potential *V*. Using Δ to represent respective changes in the parameters, we can write,

$$\Delta Z / Z_0 = \Delta V / V_0 ,$$

where $\Delta V = (V - V_0) = (V_1 + V_2) - (V_{01} + V_{02})$.

Then the sensitivity at the point $\vec{r}$ is defined as,

$$S(\vec{r}) = \Delta Z / Z_0 = \Delta V / V_0 .$$

For 3D measurements a tank made of transparent acrylic sheets was filled up with saline of known conductivity to make up a 30 cm x 30 cm x 30 cm phantom. On one wall metallic electrodes (screws) were fixed as shown in figure 2. The two concentric linear TPIM arrangements thus formed are along the diagonals as shown. The separations of the electrodes are also indicated in the figure, which were the same for both the horizontal and vertical directions; 14 cm for current electrodes and 7cm for potential electrodes. Correspondingly, the effective current to current electrode separation for any of the single TPIM arrangements was 19.8 cm while the potential to potential electrode separation was 9.9 cm. At the opposite face of the phantom an electrode was fixed at the centre, to act as the common ground connection of the potential measuring system. A 10 kHz AC signal was used in this study with the current amplitude kept constant at one milliampere. The reference axes (x,y,z) for the phantom are also shown in figure 2, z pointing towards the depth, away from the electrode plane.

In order to measure the sensitivity, a spherical plastic ball of radius 1.9 cm was used as the object. It was filled with sand to make it heavy so that it does not float. The hole drilled to pour sand was sealed using wax. This insulating ball was then placed at the desired positions by hanging it with a thread from a sliding scale (a marked ruler) on top of the phantom. The ball could be moved and fixed at any point along the horizontal direction (along x-axis) by

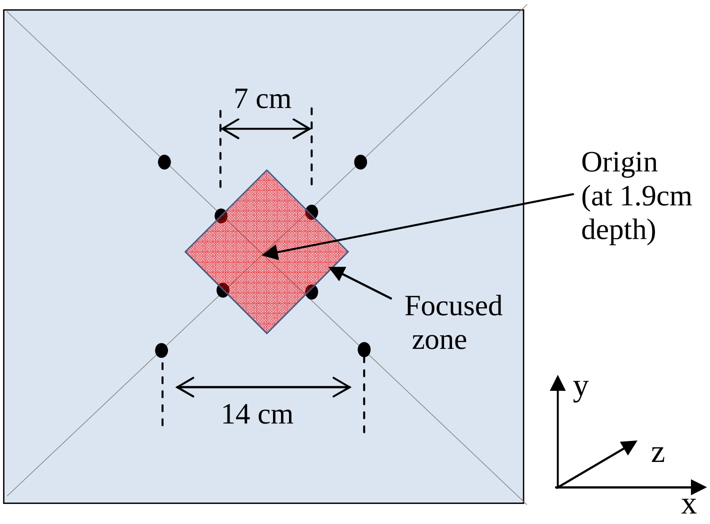

Fig. 2: Front view of phantom and electrode positions in 8-electrode FIM

changing the point of suspension on the ruler. By changing the length of the thread the ball could be fixed at any vertical position (along y-axis). Again, the ruler could be moved back and forth along the depth to fix the z-position of the ball.

To study the degree of focusing, sensitivity of points inside the focused zone as well as in the neighbouring regions were measured placing the object at various points in the phantom. The object's center was taken to represent its position. The reference co-ordinates for positioning of the object are also indicated in figure 2. The z-axis passed through the point of intersection of the lines joining the linear arrangements of electrodes. The origin of the coordinate system was taken at a depth of 1.9 cm inside the phantom. Since the radius of the ball was 1.9 cm, it is the minimum distance possible for the centre of the object from the wall.

3. RESULTS AND OBSERVATIONS

The variation of sensitivity as defined above, in the xy-plane for z=0 (1.9cm below the electrode plane) is shown in figure 3. Here the variations of sensitivity (in arbitrary units, a.u.) along x-axis for a few y-values are shown. There is symmetry about the x=0 plane which is expected due to the symmetry of the 8-electrode FIM arrangement. The focusing is also evident for y=0 and y=4cm planes for which the sweep points fall within the focused zone (Fig.2). However, the sweep points fall outside the focused zone for y=8cm which is demonstrated by the small sensitivity values in the middle.

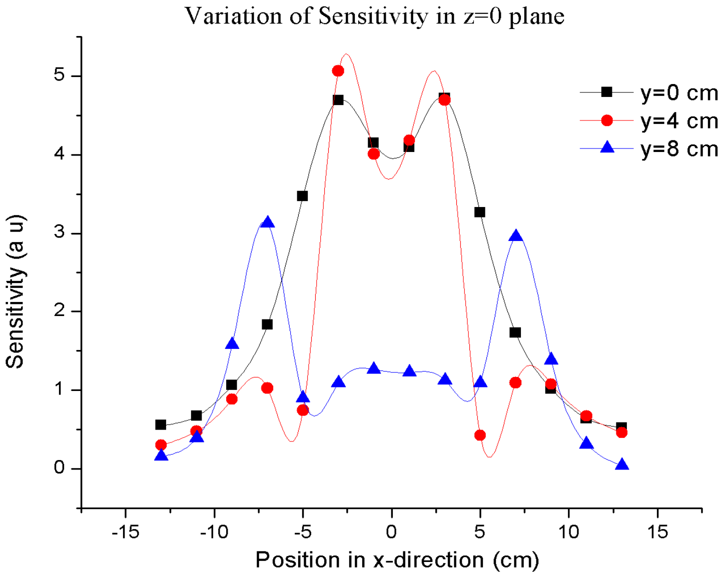

Figure-3: Variation of sensitivity when an insulating object is moved along x-axis at three y values, all for z=0 (centre of the ball at 1.9cm from the wall of the phantom).

Small peaks in sensitivity can be seen in all the three curves which correspond well to the positions of both current and potential electrodes. This is also suggested in the point sensitivities computed in earlier work (Islam et al 2010) which indicates high sensitivities near both current and potential electrodes. For y = 4 cm, two small peaks due to potential electrodes (the ones closer to the centre) and another two for current electrodes are present,

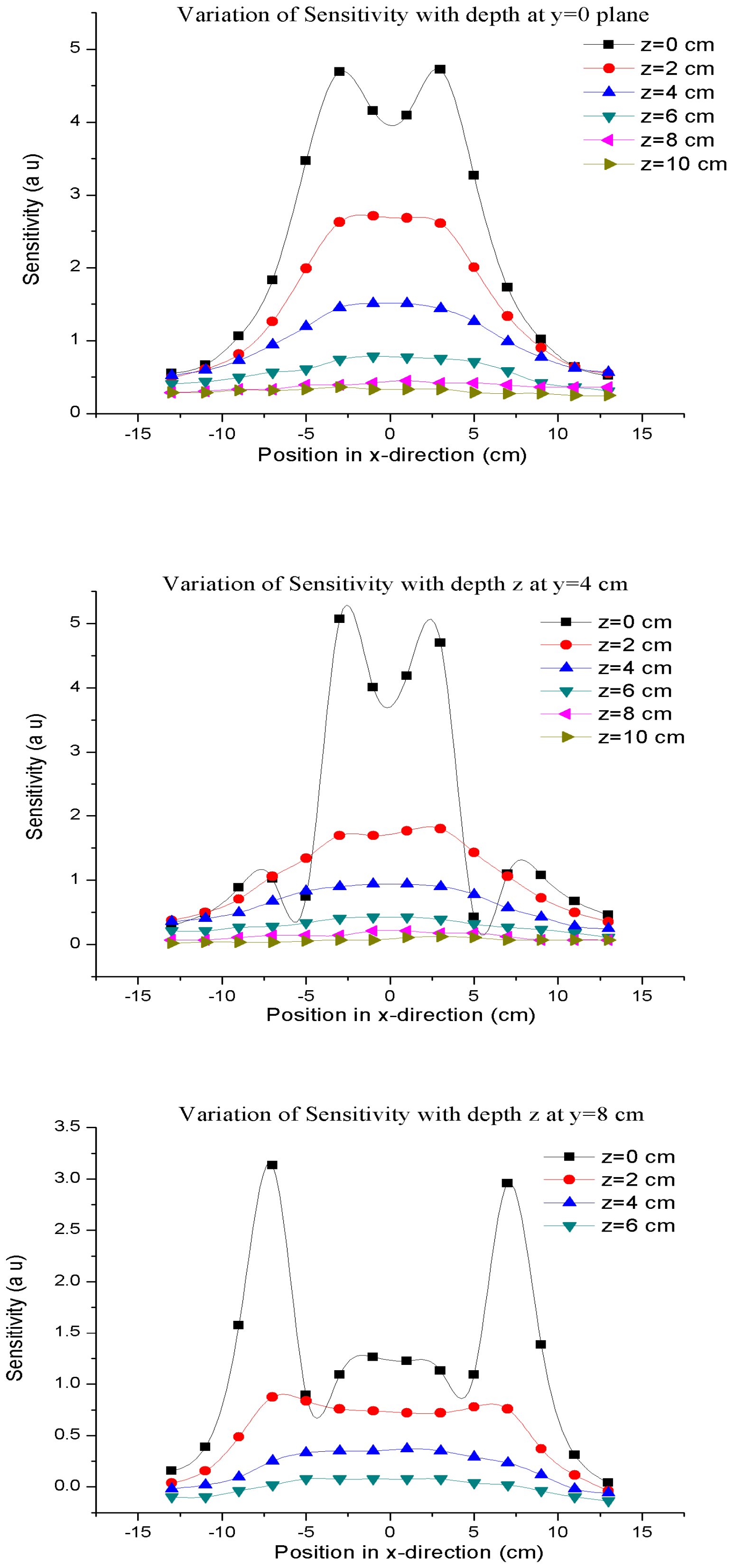

Figure-4: Variation of sensitivity with depth and lateral positions at different horizontal planes (y-fixed at 0, 4cm and 8cm) but for y = 0 cm, that due to the current electrodes are absent. It should be noted that the zones between the potential electrodes and the current electrodes just outside the focused zone has negative sensitivity (Islam et al 2010). Thus the positive sensitivity due to the current electrodes may have been annulled by the negative sensitivity in this region resulting in the absence of the peaks. For y=8cm, the peaks due to the current electrodes dominate because of proximity of these electrodes. However, the two inner peaks almost disappear in the y=8 cm plot. This can be attributed to a larger distance from the potential electrodes.

Figure 4 shows three sets of plots for y=0, 4 and 8 cm respectively to demonstrate the variation of sensitivity along x-axis for different depths (z=0 to 10cm). In all these graphs there is a symmetry about x=0 plane as before. The sensitivity values in the central segments decreases with depth (increasing z values) for all the three sets, however, that for y=0 and y=4 cm have significantly higher values compared to that for y=8 cm as the former two are within the focused zone while the latter lies outside. The behavior of the plots for z=0 has already been discussed in relation to figure 3 above. It can also be observed that for y=0 and 4 cm, the enhanced peaks due to the potential electrodes almost vanish for z=2 cm and beyond. This indicates that the focused zone is better defined, i.e., without any peaks for depths greater than 2 cm, which is favourable for real life measurements. Again at y=8 cm for large x-values (on both sides), slightly negative values of the sensitivity appeared. Although these points are beyond the current electrodes geometrically where negative sensitivity is not expected, this is possible due to outward curvature of equipotential surfaces with depth in the volume conductor, so that situations existing in the negative potential zone at the surface exists further outward with depth. Of course the overall sensitivity values are very small in this region.

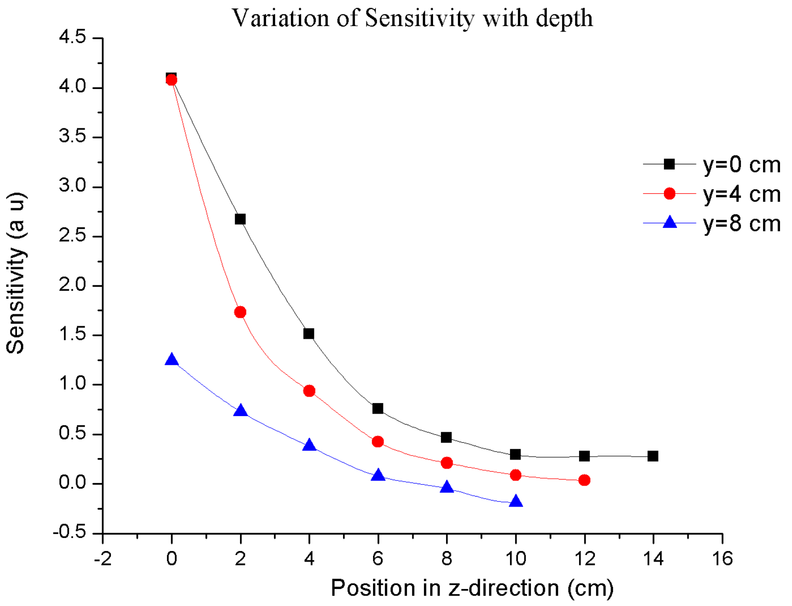

Figure-5: Variation of sensitivity with increase of depth on the yz-plane at different heights (y-values).

To get a better understanding of the variation of sensitivity with depth, the data points at x= 0 cm for different depths (z-axis) were plotted for the three y-values given in the previous plots. In all three cases, sensitivity decreased monotonically with increase of z. Again for higher values of y, sensitivity showed systematic decrease, as expected. The plot at y=0 also has similar nature to that obtained by (Iquebal and Rabbani 2010) for the 6-electrode FIM. It can be seen that the sensitivity value drops to about 10% of its value for z=0 at about z= 9 cm. Relating this with the current electrode separation of 19.8 cm and potential electrode separation of 9.9 cm gives an idea of the level of depth down to which useful measurements may be carried out using 8-electrode FIM with different dimensions.

4. DISCUSSION

An ideal focusing would be where sensitivity is high in the focused zone and zero elsewhere. Practically it would not be so and some sensitivity will also be obtained in the neighbouring zones, but these should be as small as possible.

A great many applications of FIM in medicine will involve targeting objects at a depth within the human body, which is a volume conductor. Therefore, this work will help in assessing the appropriate separation of electrodes for organ at a particular depth and for an understanding of the effect of the organ in the overall measurement. Of course, in most of the measurements a physiological change in the organ is looked for which eliminates the effect of the surrounding tissues that does not undergo the specified changes, which will also be aided by this increased understanding. The successful focusing effect observed in the present work verifies all previous findings related to FIM. Thus, this work in conjunction with the earlier work on the 3D effects of 6-electrode and 4-electrode FIM will contribute greatly to their use, and in choosing the right version of FIM for a particular application.

Some of the earlier analytical or numerical solutions were done for point sensitivity for a semi-infinite medium while the present work is based on the effect of a small object in a phantom which will represent more realistic conditions. However, since the volume conductor is large compared to the object size and the electrode separations, the overall nature of the sensitivity values are similar. The graphs shown should be symmetric with respect to the yz plane (+ve x = -ve x) which we have observed as well. This gives us confidence that our measurements obey the geometrical symmetry of the setup. Furthermore, since the setup is also symmetric with respect to the xz-plane, data were taken only for positive y-values; we expect a similar behavior for negative y-values as well.

From our 3D observations on the 8-electrode FIM system it is clear that at a particular depth within the focused zone the sensitivity is more or less uniform except at very shallow depths where the effect of the electrodes created some unevenness through the peaks. It may be anticipated that for larger objects the peaks will smear out more. It also needs to be seen how the size of the electrodes affect the magnitude and spread of these peaks. The uniformity of sensitivity within the focused zone is a very desirable property of FIM; within the focused zone if a target object moves a little laterally the measurement will not change significantly. However, the measurement is very sensitive with depth as can be seen in figure 5. Therefore, one has to take care in assessing the depth of the object and in keeping the depth constant during a measurement as much as possible.

The decrease of the depth sensitivity may be explained from two viewpoints. From a current density viewpoint it is less at greater depths, therefore the sensitivity is less. An inhomogeneity in the form of an insulating object of the same volume will perturb the current paths positioned at greater depth less. From the viewpoint of equipotentials at the potential electrodes, these are curved surfaces which bend outwards from the centre with depth increasing the dimensions of the focused zone. Therefore at shorter depths the object covers a greater proportion of the focused zone while this coverage is less at greater depths, resulting in the reduced sensitivity.

As the depth increases the rate of change of sensitivity becomes less, albeit with a small value. Therefore, at greater depths slight uncertainty in the depth will result in less uncertainty in the impedance measured. We, therefore, suggest that if there is a possibility of uncertainty in depth it is better to have the object at some distance in the 3rd dimension. Of course this will require more sensitive and improved low noise instrumentation since the sensitivity values are very much reduced. Hence, we may have to optimize for each organ by adjusting the separation of the driving and measuring electrodes depending on the assumed position of the organ in the 3rd dimension. Both these separations will have effects on the volume sensitivity. At smaller depths the curve is more non-linear and we may need to calibrate them for such variations.

The present work gives a better understanding of the sensitivity of 8-electrode FIM. This will improve confidence in the use of the essentially two dimensional FIM system for measurements of impedance of objects placed in the third dimension and will justify the use of the system for studying organs at depths from the skin surface paving the way for better clinical applications.

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References:

Brown BH, Wilson AJ & Bertemes-Filho P. 2000. Bipolar and tetrapolar transfer impedance measurements from a volume conductor. *Electron. Lett*, **36**. 2060–2062. http://dx.doi.org/10.1049/el:20001439.

Geselowitz DB. 1971. An application of electrocardiographic lead theory to impedance plethysmography. *IEEE Trans. Biomed. Eng.* 38-41. http://dx.doi.org/10.1109/TBME.1971.4502787.

Iquebal AHM & Rabbani KS. 2010. 3D sensitivity of 6-electrode Focused Impedance Method (FIM). *J. Phys.: Conf. Ser. (IOP)*, **224**. http://iopscience.iop.org/1742-6596/224/1/012156.

Islam N, Rabbani KS & Wilson AJ. 2010. Sensitivity of focussed electrical impedance measurements. *Physiol. Meas.*, **31**. S97–S109. http://iopscience.iop.org/0967-3334/31/8/S08/.

Karal MAS & Rabbani KS. 2010. Sensitivity of the new four-electrode Focused Impedance Measurement (FIM) system for objects with different conductivity. *Dhaka University J. of Science*, **58**. 45-47.

Pethig R 1979. *Dielectric and Electronic properties of Biological materials.* Wiley J, NY, USA.

Rabbani KS & Karal MAS. 2008a. A new four-electrode Focused Impedance Measurement (FIM) system for physiological study. *Annals of Biomedical Engg*, **36**. 1072-1077. http://link.springer.com/article/10.1007%2Fs10439-008-9470-7.

Rabbani KS & Karal MAS. 2008b. Variation in sensitivity within the focused zone of the new four-electrode Focused Impedance Measurement (FIM) system. *Dhaka University J. of Science*, **56**. 1-6.

Rabbani KS, Sarker M, Akond MHR & Akter T. 1999. Focused Impedance Measurement (FIM) a new technique with improved zone localization. *Annals of the new York Academy of Science, Electrical Bioimpedance Methods*, **873**. 408-420. http://onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.1999.tb09490.x/pdf.

Schwan HP 1957. *Electrical properties of tissue and cell suspensions*. Lawrence J & Tobias C, **5**, 147-209. San Diego, CA, Academic Press. http://dx.doi.org/10.1016/B978-1-4832-3111-2.50008-0