Improved Understanding of the Sensitivity of Linear Tetrapolar Impedance Measurement (TPIM) and 8-Electrode Focused Impedance Method (FIM) in a Volume Conductor

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Abstract

Tetrapolar Impedance Measurement (TPIM) is a 4-electrode impedance measurement system appropriate for a volume conductor in which current is driven through a pair of electrodes while potential developed across another pair of electrodes is measured to provide a value of transfer impedance. The 8-electrode Focused Impedance Method (FIM-8) consists of two concentric and orthogonal linear TPIM systems with their transfer impedances added for the purpose of localizing the central zone. Detailed 3D sensitivity studies are necessary for proper application of the techniques in specific biomedical applications and most reported work present point sensitivity distributions. The present work mainly focuses on planar average sensitivity in planes parallel to the electrode plane and its variation with depth due to different combinations of electrode separations – both for current drive pair and the potential measuring pair. This was obtained through finite element simulation using COMSOL Multiphysics software for a 40x40x40cm^3 volume. The results give useful information that can be used to design electrode configurations and measurement modalities for various applications.

Keywords: Electrical Impedance, Localized impedance, TPIM, FIM, Finite Element Method, Planar sensitivity.

Introduction

Electrical Impedance techniques have potential in many areas of biomedical applications. Among the simplest techniques, Tetrapolar Impedance Measurement (TPIM) and Focused Impedance Method (FIM) are the two most popular ones. A typical linear arrangement of electrodes in a traditional Tetrapolar Impedance Measurement (TPIM) method is shown in Figure 1. Here current is passed through a pair of current drive electrodes (CC-1 and CC-2) and potential is measured across another pair (PU-1 and PU-2). A value of transfer impedance (Brown et al, 2000, Martinsen and Grimnes, 2009) is obtained dividing the potential *V* by the driven current *I*.

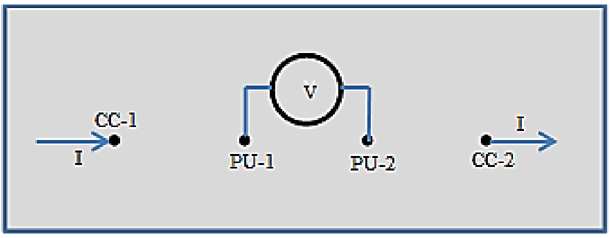

Fig-1: Electrode configuration in traditional Linear Tetrapolar Impedance Measurement (TPIM) system.

Focused Impedance Method (FIM) was conceived by the Bio-medical physics group in the department of Physics of the University of Dhaka (Rabbani et al. 1999, Rabbani and Karal, 2008). It has three versions having 8, 6 and 4 electrodes respectively. The 8-electrode FIM essentially consists of two concentric orthogonal linear TPIM Systems where the individual transfer impedances are averaged to give enhanced sensitivity in the central region. The electrode configuration is shown in Figure 2. Here CC-1 and CC-2 are the current drive electrodes and PU-1 and PU-2 are the potential measuring electrodes for the first TPIM giving V_1 as the measured potential. Again, CC-3 and CC-4 are the current drive electrodes for the second TPIM for which PU-3 and PU-4 are the potential measuring electrodes giving V_2 as the measured potential. Typically both driven currents have the same value so that the transfer impedance in FIM is given by $(V_1+V_2)/I$. This has enhanced contribution from the central region for which it is said to be focused. This can be used effectively to localize organs or objects of interest in volume conductors like the human body.

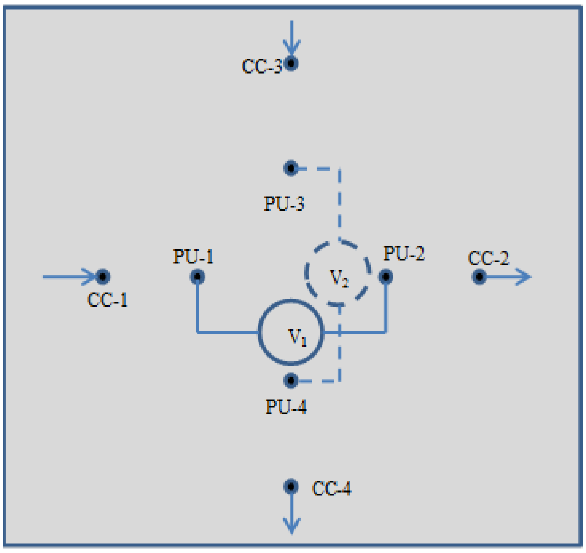

Fig-2: Electrode configuration in 8-electrode FIM. It is essentially two linear TPIM systems placed orthogonally.

An understanding of the 3D sensitivity in a volume conductor of the above two measurement configurations would be useful in a choice for particular applications. This paper particularly concentrates on the variation of planar average sensitivity at different depths for different separations of current drive and potential electrodes.

The sensitivity (S) of a particular point within a volume conductor in TPIM is given by the dot product of two current density vectors divided by the current squared (Martinsen and Grimnes 2009),

$$S = \frac{\vec{J}_1 . \vec{J}_2}{I^2} \quad \dots (1)$$

Where $\vec{J}_1$ is the current density at the specified point due to a constant current I driven through the pair of CC electrodes and $\vec{J}_2$ is the current density at the same point with the same constant current driven through the pair of PU electrodes.

For FIM, the transfer impedance was defined as the summation of the two orthogonal transfer impedances. Therefore, the sensitivity at any point for FIM was also defined as the sum of the sensitivities at that point due to the two orthogonal TPIM measurements (Islam et al, 2010).

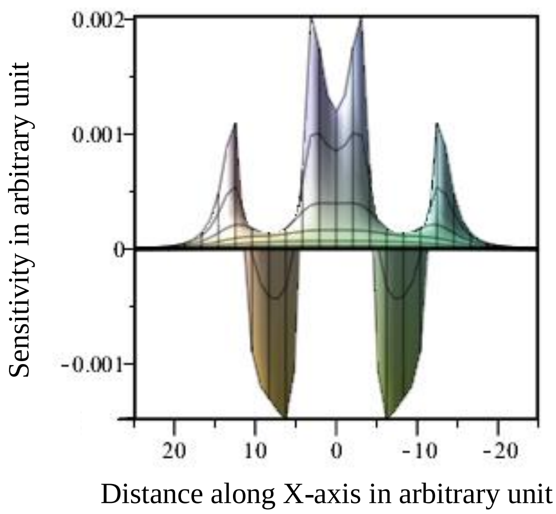

Fig-3: Numerical sensitivity of TPIM. Coordinates for CC electrodes were (-12, 0) and (12, 0) while that for PU electrodes were (-4, 0) and (4, 0). The negative sensitivity is seen at the regions between the CC and PU electrodes.

A typical sensitivity pattern for TPIM at a depth very close to the electrodes is shown in Figure 3. It can be seen that it has a large negative sensitivity between the CC and PU electrodes on each side. This means if an object with a higher impedivity than that of the background is placed between the PU electrodes at the centre, the measured transfer Impedance will be greater than that measured for the background only. On the other hand if the same object is placed between the CC and PU electrodes on either of the two sides, the measured transfer Impedance will be smaller than that measured for the background only. Besides being asymmetric, the width of the sensitivity zone in 2D is expected to spread away from the line joining the electrodes in TPIM.

In order to limit the sensitivity zone at the centre, Focused Impedance Method (FIM) was proposed and successfully implemented in 2D (Rabbani et al 1999). Since then a number of papers reported the sensitivities of FIM in 2D and 3D (Abir et al, 2014; Islam et al, 2010; Iquebal and Rabbani, 2010; Saha et al, 2013) and its possible application in physiological studies and diagnosis in the areas of gastric emptying, lungs ventilation, breast tumour characterization, abdominal fat thickness measurement, etc., (Ahmed et al, 2014; Al-Quaderi et al, 2014; Amin et al, 2014; Ferdous et al, 2013; Howlader et al, 2010; Rabbani and Kadir, 2011; Surovy et al, 2012).

However, for a proper application to investigate particular geometries and situations in the human body it is necessary to have a thorough understanding of the methods that are being used.

In many applications the overall sensitivity of a plane at a certain depth is of concern rather than a point sensitivity distribution which most reports deal with. Besides, in both TPIM and FIM, the separation of CC and PU electrodes are of particular concern. The sensitivity patterns are expected to vary significantly with these parameters. This paper investigates the variations in planar average sensitivity with depth for different separations of CC and PU electrodes both for TPIM and FIM using finite element simulation which helps in improved understanding while analyzing a particular experimental result.

Methods and Materials

For the present work a finite element based software package known as 'COMSOL Multiphysics' was used (ac/dc module, version 4.3a). A cube shaped phantom (40x40x40cm^3) was taken to be the bulk conductor with conductivity and relative permittivity as 1S/m and 10 respectively. Copper electrodes of 1cm diameter were placed on one surface of this cubical volume. An alternating current with a frequency of 5 KHz and constant amplitude of 1A was applied to the current driving electrodes.

From COMSOL Multiphysics, the pixel level values of sensitivity were exported to a worksheet using which the planar average sensitivity within the bulk volume considered (40 cm cube) were calculated for different planes parallel to the electrode plane, at different depths. Planar average sensitivity values were calculated for 11 planes starting from zero depth, i.e., at the electrode plane, to a depth of 10cm below electrode surface, at 1cm intervals. The planar average sensitivity values were then plotted against depth for different Electrode separations. In the present work, two sets of readings were taken, in the first, the PU electrode separation was kept fixed at 6cm for both TPIM and FIM and the CC electrode separations were taken as 12cm, 14cm, 16cm and 18cm respectively. In the other set, the CC electrode separation was kept fixed at 18cm while the PU electrode separations were taken at 6cm, 8cm, 10cm and 12 cm respectively

Simulation was also performed to study the variation at small depths in a greater detail, from zero to 0.25cm at 0.05cm intervals. The results are given in the next section.

Results and Observations

Typical 2D sensitivity distributions for TPIM and FIM, as obtained using this simulation are shown in Figure 4. For these plots the separation of the CC electrodes was 18cm and that of the PU electrodes was 6cm, and the figures show the point sensitivity distribution in a plane at a depth of 3cm from the electrode plane.

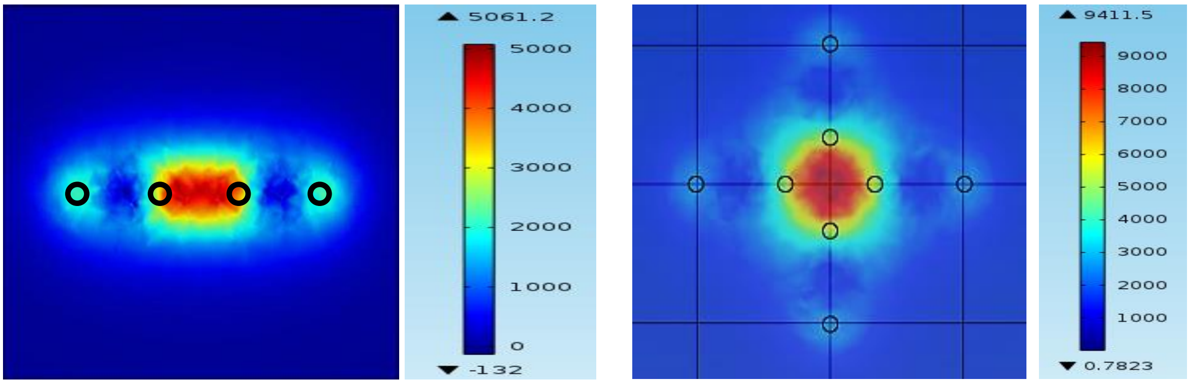

Fig-4: Point sensitivity distribution for TPIM (left) and FIM (right) at 3cm depth below electrode surface as simulated in Comsol Multiphysics software. For both, the CC electrode separation was 18cm and PU electrode separation was 6cm. The electrode positions are indicated by the superimposed circles. The FIM gives a symmetric localization of sensitivity.

Negative sensitivity can be seen at regions between the CC and PU electrodes for TPIM, but not for FIM. This can be appreciated from the minimum values shown numerically at the base of the colour bar, which are -132 and +0.7823 respectively. In FIM, positive sensitivity due to one configuration of TPIM cancels out the negative sensitivity due to the other orthogonal configuration. However, it will be shown later that negative sensitivity exists to some extent at shallower depths. The symmetry of FIM is also to be noted. Both of these factors make FIM a useful modality for measurement for practical applications.

For the planar average sensitivity, the results obtained for TPIM and FIM for a constant PU electrode separation of 6cm and for different CC electrode separations (indicated in the figures) are shown in Figures 5 and 6 respectively. It can be seen that for a CC separation of 12cm, the peak value occurs at the same value for both TPIM and FIM. This is expected because of the close relationship between TPIM and FIM. In this case the separation between the CC and PU electrodes (CC-PU separation) on each side is 3cm [= (12-6)/2] while the peak value occurs at about 1cm, at about 1/3rd the CC-PU separation. This was also observed by others (Brown et al, 2000, Islam et al 2010). The positions of the peaks at the other CC separations also support this observation.

As mentioned above, for the FIM, the sensitivity values for the two orthogonal TPIM configurations were summed, therefore, the numerical values for FIM are higher than the corresponding ones for TPIM, being almost double. However, an interesting variation may be observed in the magnitude of negative sensitivity at shallow depths. For TPIM with fixed PU of 6cm, the negative value is high for 12cm CC electrode separation. It then vanishes and starts with a high positive sensitivity for 14cm CC separation, and again decreases and goes towards a negative value for 18cm CC separation. For FIM, the behavior is similar but the negative value is much smaller, in comparison with respective positive values.

Another point worth noting is that the variation of the values with depth goes down with increasing CC separation, giving a more uniform sensitivity over a range of depth, which may be useful in certain situations.

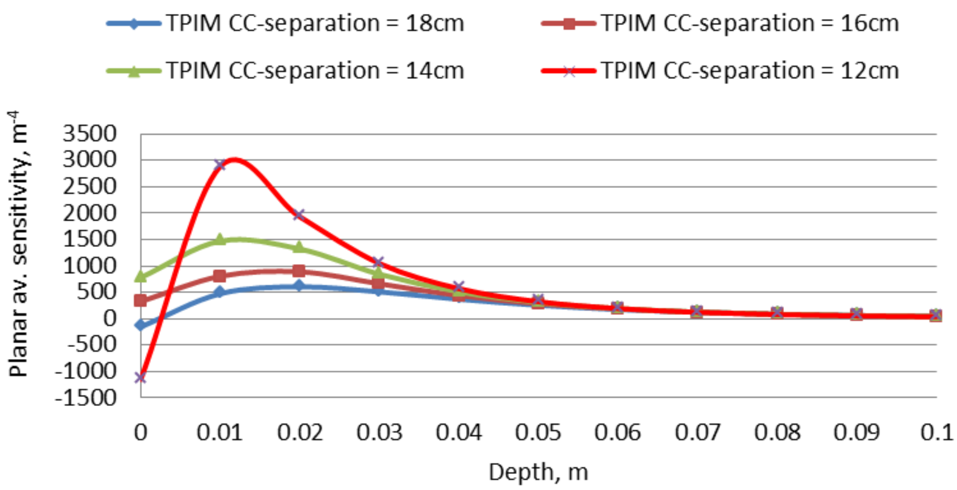

Fig 5: Planar average sensitivity for TPIM, plotted against depth for different CC electrode separations with a constant PU electrode separation of 6cm

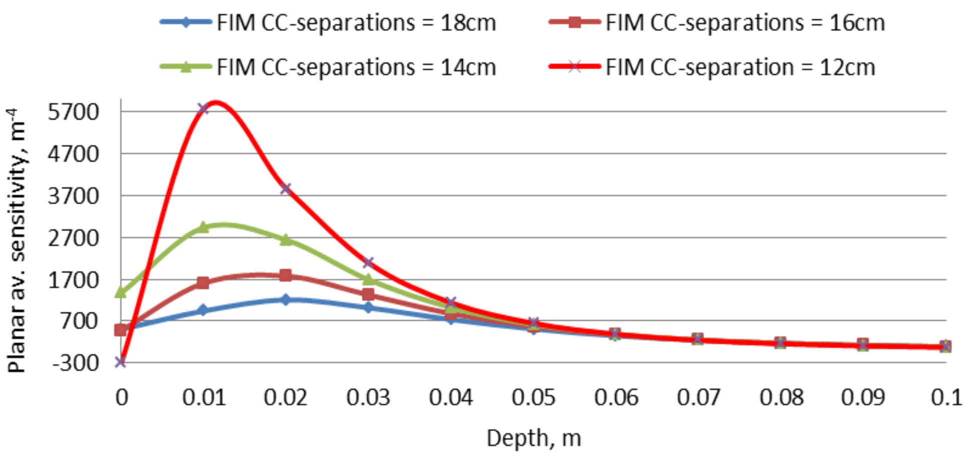

Fig 6: Planar average sensitivity for 8-electrode FIM, plotted against depth for different CC electrode separations with a constant PU electrode separation of 6cm.

Figure 7 and 8 shows the planar average sensitivities for both TPIM and FIM respectively for different PU electrode separations with a fixed CC electrode separation of 18cm. This also shows the interesting aspects with respect to negative sensitivity at shallow depths. The sensitivity goes towards negativity from a PU separation of 6cm to about 10cm after which it becomes positive at 12 cm. In this case, the magnitude of negative sensitivity is more in FIM than in TPIM, in contrast with that obtained in Figures 5 and 6 respectively.

Figures 9 -12 shows the details of the planar average sensitivities for similar conditions as for Figures 5-8 respectively but for shallow depths only, less than 0.25cm. The behaviours appear anomalous, without any specific trend.

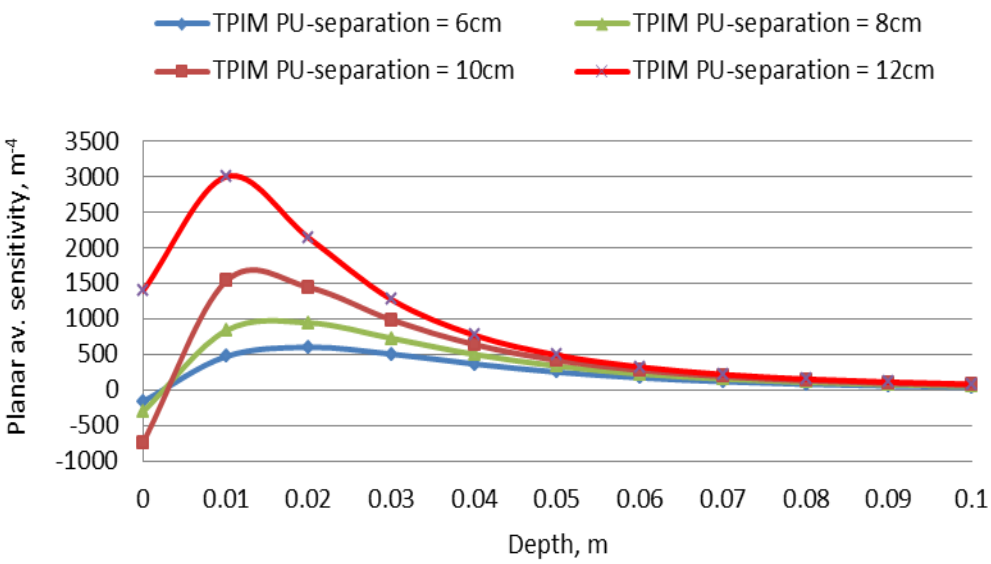

Fig 7: Planar average sensitivity with depth for TPIM for different PU separations. The CC electrode separation was fixed at 18cm.

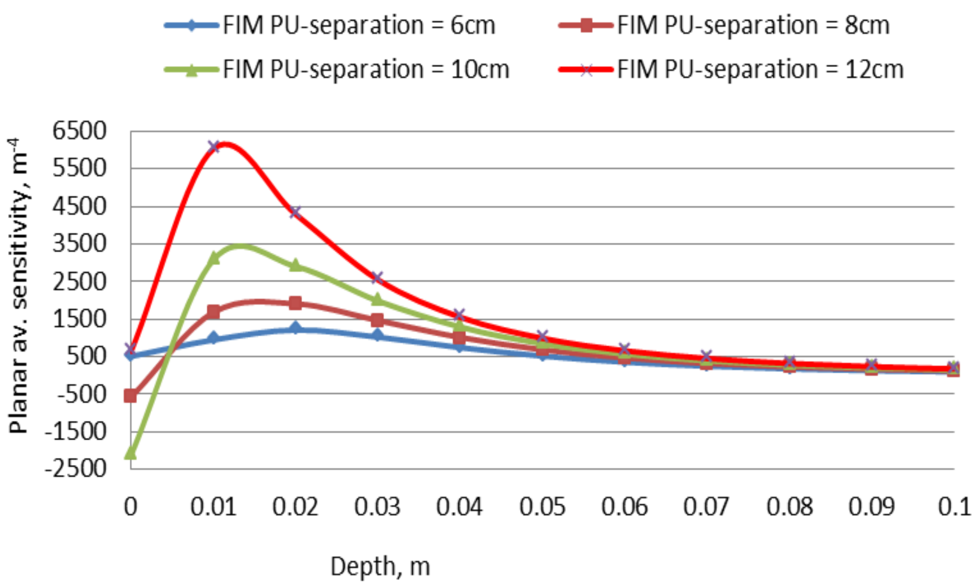

Fig 8: Planar average sensitivity with depth for 8-electrode FIM for different PU separations. The CC electrode separation was fixed at 18cm.

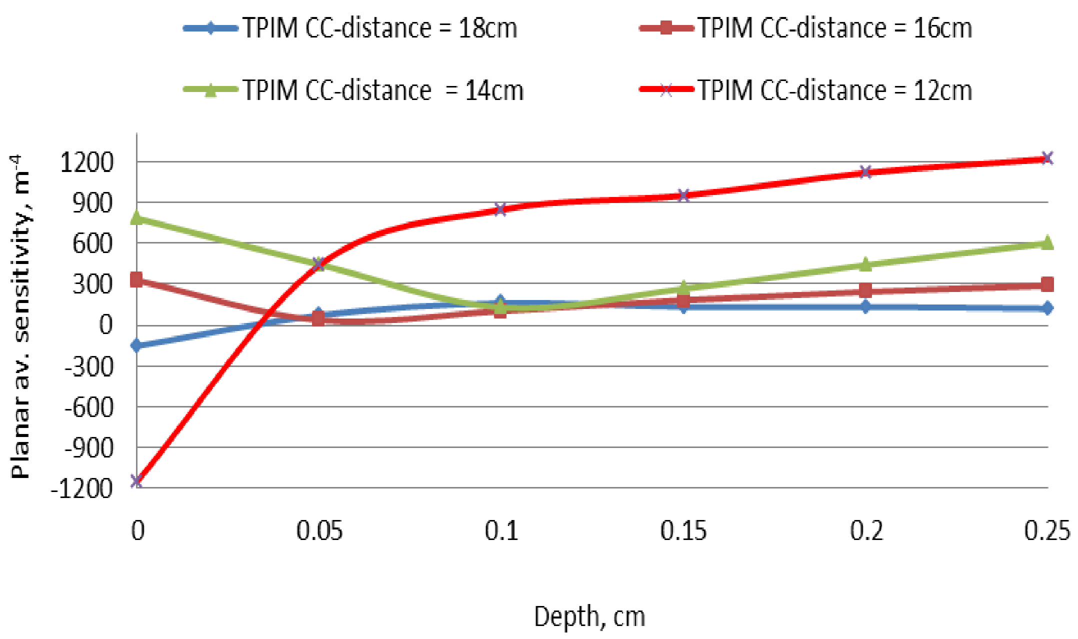

Fig 9: Details of planar average sensitivity with depth for TPIM at shallow depths, less than 0.25cm, for a fixed PU electrode separation of 6cm. It looks anomalous, because of several factors, including the electrode geometry.

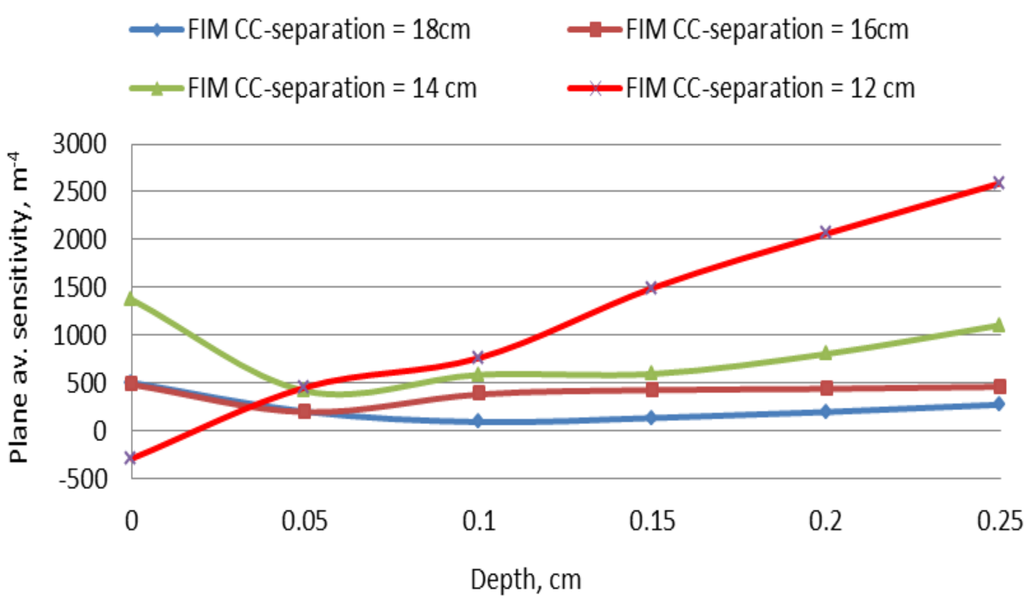

Fig 10: Details of planar average sensitivity with depth for FIM at shallow depths, less than 0.25cm, for a fixed PU electrode separation of 6cm.

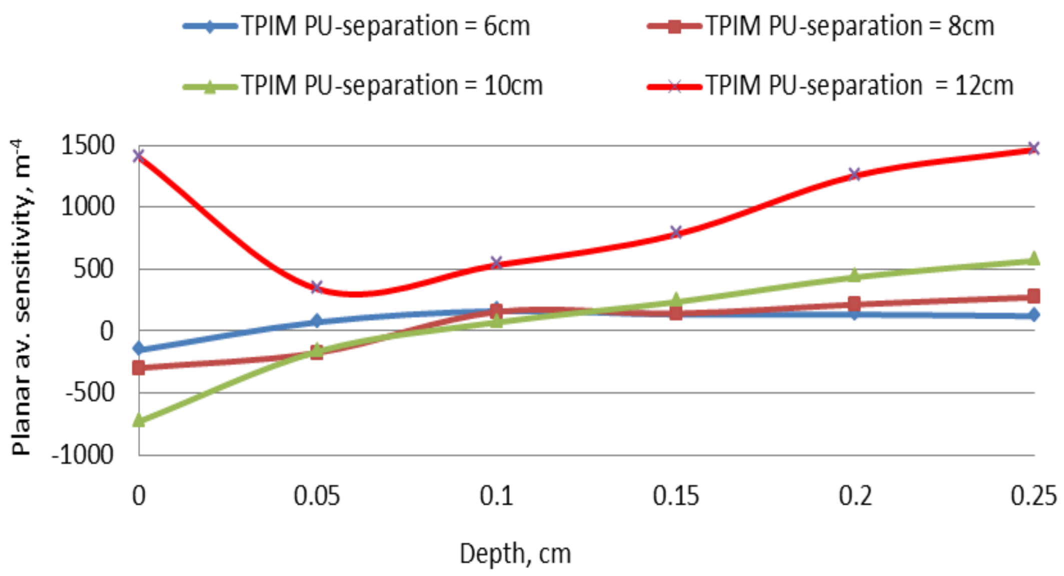

Fig 11: Details of planar average sensitivity with depth for TPIM at shallow depths, less than 0.25cm, for a fixed CC electrode separation of 18cm.

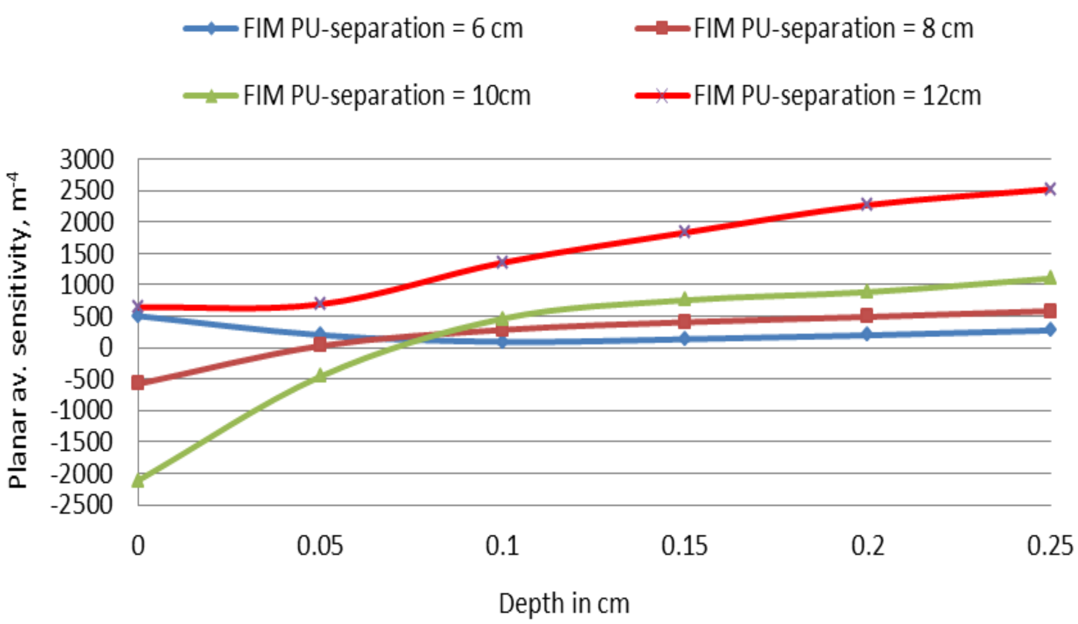

Fig 12: Details of planar average sensitivity with depth for FIM at shallow depths, less than 0.25cm, for a fixed CC electrode separation of 18cm.

Discussion

In view of the potential applications of electrical impedance methods in Biomedical applications such systems should be understood and studied in detail. The present study looked into the effect of changing the current drive and potential electrode separations on TPIM and 8-electrode FIM systems, particularly for the planar average sensitivity at different depths for planes parallel to the electrode plane. Figures 5 to 8 show that for fixed CC electrode separation, as the separation between CC and PU electrodes decreases, the change in sensitivity with depth is more pronounced, with a peak value at one third of the CC-PU separation. This may be used intelligently to design TPIM and FIM systems to target a thin object at a particular depth. On the other hand if one desires to obtain an overall uniform sensitivity with depth, for objects that are extended in the 3rd dimension, a large CC-PU separation may be chosen.

Again, Figures 9 to 12 suggest that at very shallow depths, less than 0.25cm in these examples, the variation of planar average sensitivity with depth is anomalous, which may be due to the close proximity of electrodes as the electrode geometry may have a significant effect. Therefore, it is better to avoid targeting objects at such shallow depths with large electrodes, which in this case had diameters of 1cm.

Again, the point sensitivity distributions shown in Figure 4 support the primary conceptualization of FIM; FIM is indeed a better measurement to look for when studying a localized region or a localized object.

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