Application of Focused Impedance Method (FIM) to Determine the Volume of an Object within a Volume Conductor

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Abstract: Focused Impedance Method (FIM), a new technique of electrical impedance measurement having high sensitivity in the central region, can sense the change in transfer impedance of an object embedded at a shallow depth within a volume conductor of unchanging background conductivity, using electrodes at the surface. This paper presents a new method for measuring the volume of such an embedded object using two electrode separations of a concentric 4-electrode FIM configuration. The formalism developed requires the depth of the object to be known, which is possible using anatomy for objects in the human body, the main target of this research. The new method has been evaluated for a spherical object in a cubic volume conductor using COMSOL Multiphysics software simulations that use finite element method. The error in the evaluated radius of the object was less than 1%. Further studies using phantoms will be performed before applying this technique on human subjects for the measurement of the volume of acid secretion in the stomach and similar applications.

Keywords: Electrical Impedance, FIM, Volume determination, Sensitivity distribution, Volume Conductor, Gastric acid secretion.

1. Introduction

Electrical impedance techniques have attracted scientists over many years for physiological study and diagnosis as human body is a volume conductor [1,2,3,4,5]. In a typical tetra-polar electrical impedance measurement, an alternating current of constant amplitude is injected into a volume conductor through a pair of surface electrodes and the resulting voltage across another electrode pair is measured. The ratio of the measured voltage to the injected current gives the transfer impedance of the volume conductor for a particular electrode configuration [6]. The extent to which a change in conductivity of a point within the volume conductor contributes to the measured transfer impedance is defined as the sensitivity. In order to determine the point sensitivity, reciprocity theorem is invoked which essentially says that if the current and the potential electrode pairs are interchanged in the above system, the measured values remain the same. Therefore the sensitivity may be determined considering only current driven through both the pairs of electrodes. Thus if J1 and J2 are the current density vectors at a point within the volume conductor due to injection of current I through the exciting and sensing electrode pairs respectively, then the sensitivity of the point is defined as [6,7],

$$Sensitivity = \frac{J_1 \cdot J_2}{I^2} \qquad \ldots (1)$$

Focused Impedance Method (FIM), an innovation of our extended group at the University of Dhaka [8] has localized sensitivity distribution [9], and hence can measure the change in transfer impedance of a specified target zone within a volume conductor minimizing the contribution from its neighbours. The basis of the new FIM technique is that the impedance of the region of interest is measured along two mutually perpendicular directions giving a higher sensitivity in the central region compared to its surroundings. It has three versions using 8, 6 and 4 electrodes respectively. The present work was taken up to determine the volume of an object embedded in a volume conductor with a different but uniform conductivity using 4-electrode FIM placing electrodes on the surface of the volume conductor.

Determination of in vivo organ volume is of great importance both for evaluation and management of physiological disorders. For example, determination of the thyroid gland volume is essential for proper diagnosis and therapy. Again, the volume of acid secreted in the stomach needs to be measured for diarrhoeal research. Aiming potential applications in estimating volume of organs within human body, we propose a new method based on FIM to determine the volume of an object embedded in a volume conductor, developed with the help of COMSOL finite element simulation entirely.

2. Materials and Methods

A cubic tank of edge 30cm filled with saline was modeled as a volume conductor in COMSOL Multiphysics with cylindrical electrodes of diameter 1cm and thickness 0.2cm placed on one of the sides, centrally (figure 1, front surface, shown transparent).

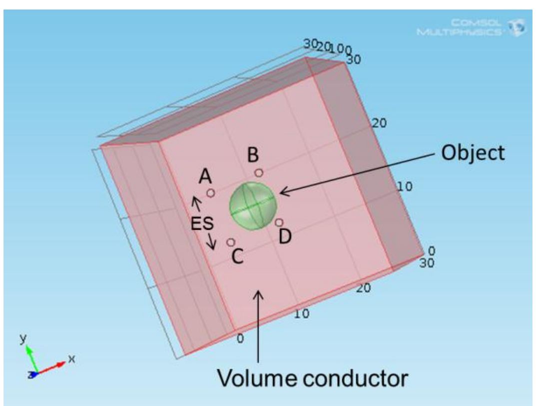

Figure 1: COMSOL model used in the volume determination study. A spherical object is embedded in a volume conductor. Electrodes are placed at the front surface of the volume conductor which is shown transparent.

In FIM, since the current and potential electrodes are interchanged orthogonally and the results added, the FIM point sensitivity will be given by the addition of the two orthogonal point sensitivities as given in equation 1. Thus if J_{ec}, J_{ec2}, J_{ec3} and J_{ec4} are the current density vectors at a point within the volume conductor for injection of current I through the electrode pairs (A-B), (C-D), (A-C) and (B-D) respectively, then the FIM sensitivity at the point is given by

$$FIM\ Sensitivity = \frac{J_{ec} \cdot J_{ec2} + J_{ec3} \cdot J_{ec4}}{I^2} \quad \ldots (2)$$

In the COMSOL model, alternating current of unit amplitude (1A) was injected through the electrode pairs (A-B), (C-D), (A-C) and (B-D) simultaneously using the electric current interface in AC/DC module. The 3D sensitivity distribution of FIM was then obtained from the COMSOL Multiphysics expression [10]:

((ec.Jx*ec2.Jx+ec.Jy*ec2.Jy+ec.Jz*ec2.Jz)+(ec3.Jx*ec4.Jx+ec3.Jy*ec4.Jy+ec3.Jz*ec4.Jz))/((1[A])^2) … (3)

A spherical object of radius (r) of conductivity different from that of the saline was assumed to be placed at the center of the four electrode configurations at a depth (d) from the electrode plane. The simulated FIM measurements were taken by injecting an alternating current of constant amplitude sequentially through electrode pairs (A-B) and (A-C) using the Electric Currents (ec) interface of AC/DC module and measuring the resulting voltage difference across the corresponding Boundary Probes (C-D) and (B-D) respectively. The studies were performed in the frequency domain at 5 kHz. Focused impedance (FZ) was then derived from the sum of two tetra-polar transfer impedance values calculated from the ratio of the injected current to the measured voltage.

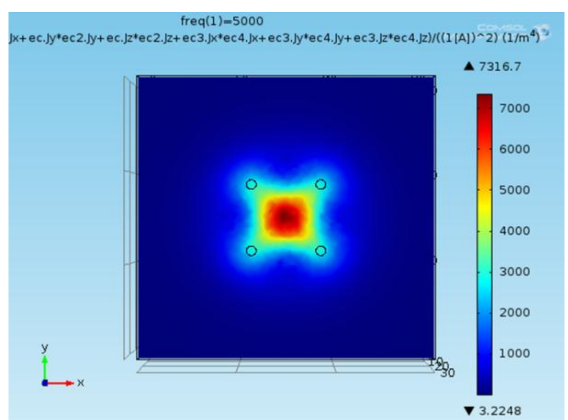

Figure 2: Sensitivity distribution of FIM at a plane at 3cm depth from the electrode plane showing enhanced sensitivity at the central zone.

3. Results and observations

Figure 2 shows the COMSOL simulated FIM sensitivity distribution for the 4-electrode configuration at a depth 3cm from the electrode plane with an Electrode Separation (ES) of 7cm. It can be seen that the sensitivity of the central zone underneath the electrodes is much higher compared to its surroundings. This zone of enhanced sensitivity is termed as Focused zone. It was also observed that the sensitivity of the focused zone decreases with increasing depth, which is expected.

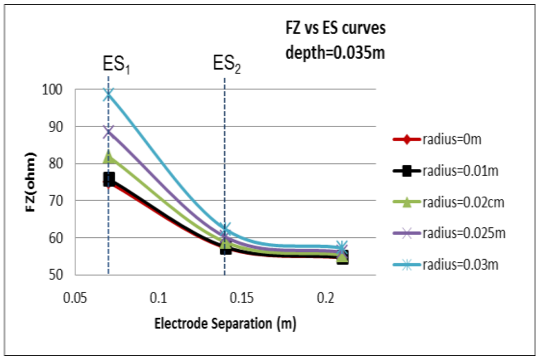

Figure 3: Change in Focused Impedance with increasing electrode separation for objects of different radius (r=0 means no object). The object depth and conductivity were kept constant

Focused impedance (FZ) of the system was obtained for various Electrode Separations (ES) with objects of different radius while the object depth and conductivity were kept constant. It was found that the FZ decreased with increased ES (figure 3), but also changed with the radius (or volume) of the embedded object, which is expected. The lowest curve, for zero object radius is that relevant to the background only.

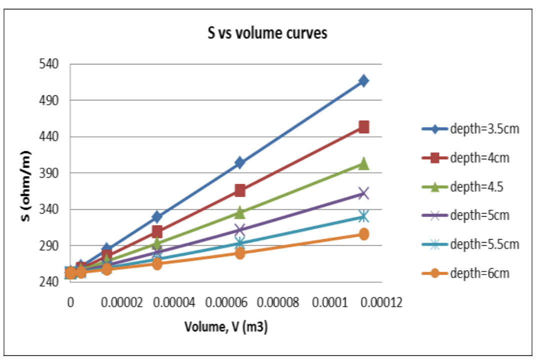

Figure 4: Relationship of S with object volume at different depth. The slope S is linearly proportional to the object volume V.

The segment of the curves in the rapidly decreasing part in figure 3 was almost linear for each embedded object (between ES_1 and ES_2). Calculating the slopes S for the different objects and plotting the slope against volume for a particular depth, it was found to have a linear dependence as shown in figure 4. This figure also shows that for different depths the plots are also almost linear and that the slopes decreased with increasing depth, a behavior well expected, eventually becoming constant for a zero object volume, i.e., for the background without any object. The intercept of all these plots also converged to this value for the background only.

Therefore, if the depth is known, such graphs may be used to determine the volume of an embedded object. A formalism was developed in the present work for this purpose as follows.

From any linear graph in figure 4, the slope S may be related to the volume V of the object as,

$$S = AV + C \qquad \ldots (4)$$

where A is the slope and C is the intercept. It can be seen that the slope decreases for increasing depths, while the intercept has the same value for all the graphs, which essentially is the background, without any embedded object. The slope A is expected to depend on the conductivity and permittivity of the object and that of the volume conductor, and also on the depth of the object.

Obtaining values for a constant object volume V in figure 4 (for the largest in the figure), a graph was plotted for A against the inverse of depth of object as shown in figure 5.

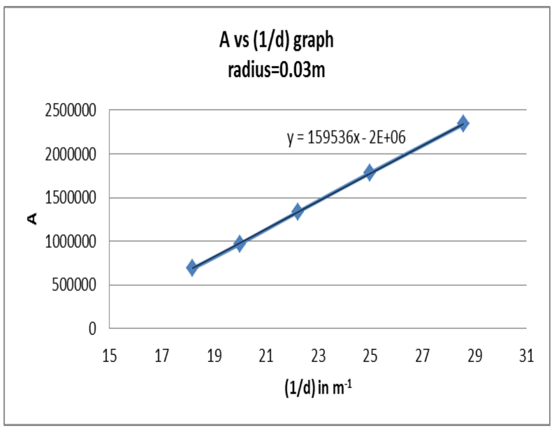

Figure 5: Relation between the slope A with object depth d. The slope A is inversely proportional to the depth.

It can be seen that this is a linear plot indicating that slope *A* is inversely proportional to depth *d*. This allows us to develop necessary formalism for the determination of an object volume at any depth as follows.

From figure 5 we have,

$$A = \frac{K}{d} + B \qquad \ldots (5)$$

where *K* is the slope and B is the intercept.

Combining equation 4 and equation 5 we have,

$$S = \left(\frac{K}{d} + B\right)V + C \qquad \ldots (6)$$

where K, B and C are constants that depend on the conductivities of the background and of the object, dimensions of the volume conductor and the electrode properties.

Therefore, volume *V* can be obtained from the slope *S* of the measured curve in figure 3 for a particular object configuration if depth *d* and the values of the other constants are determined through experimental procedures.

For a particular case as shown in figure 5, the values of the constants were estimated from COMSOL simulations. For this the following values were taken. Saline conductivity, σ_s =0.04 S/m, object conductivity, σ_o=1e-14 S/m, Electrode separations, ES_1=0.07m, ES_2=0.14m and sides of the tank, L=0.3m. Stainless steel cylindrical electrodes were assumed with diameter = 0.01m. Using these values the constants were calculated as:

K = 159536, B = – 2211400, C = 252.118

Spherical objects of different assumed volumes were assumed to be placed at different depths within the tank of the simulated COMSOL model. FIM values for two electrode separations were obtained from the simulation and the object volumes were calculated using equation 6. The corresponding radius was compared with the assumed object radius. Table 1 shows that the radius of the object has been obtained with an error less than 1%.

Table 1: Comparison of the actual object volume to the calculated volume from simulated FIM measurements taken in the COMSOL model

Simulated Radius m	Depth m	Calculated Radius m	% error
0.025	0.035	0.02489	0.44
0.030	0.045	0.03002	0.07

4. Discussions and Conclusions

The present work has put forward a new technique for measurement of the volume of an object embedded within a volume conductor using 4-electrode FIM, and verified using COMSOL Multiphysics simulation software. This technique uses two different electrode separations of FIM and for objects at relatively shallow depths from the surface. Of course this is possible if the object depth from the electrode surface is known, and in case of the human body, anatomy can provide this information. Although the study was performed only for spherical objects inserted in a homogeneous and isotropic volume conductor, the proposed noninvasive and non-ionizing FIM technique has the potential of estimating volume of an organ within the human body, for instance, estimating the food content in the stomach, or for the measurement of gastric acid secretion. Electrical resistivity methods have also been in use in Geology for mining applications [11]. The proposed method may also be used to estimate volume of subsurface mines or structures.

The simulated measurements described in this paper were performed over a limited range of object diameters and depths. The ranges used can be approximately expressed as 0<2r<ES1 and 0<d<ES1, where 2r is the diameter of the object and d is the depth of the centre of the object with respect to the electrode surface, ES1 being the smaller of the two electrode separations of the 4-electrode FIM used. Whether it is applicable to a wider range has to be found out through further work.

The close agreement between the initial assumed radius and the calculated value obtained through the simulated FIM measurement speaks of success of the new technique of FIM with two separations. It has also increased the confidence in using COMSOL package for such applications. Earlier, our laboratory was using phantom experiments mostly to verify new ideas employing electrical impedance techniques. The availability of COMSOL Multiphysics package has made the process much simpler. Besides, it can be used to obtain a large number of data within a certain range which would be very difficult in the experimental techniques. However, no theory or simulation will be acceptable unless these are verified through experimental work. Therefore, the method of volume measurement of objects embedded in a volume conductor as presented in the present work will need to be verified through carefully performed phantom experiments for confidence.

The new technique for volume measurement using FIM will have applications in many areas, in Biomedical Physics & Engineering, in Geology and in Oceanography.

5. References

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