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Determination of abdominal fat thickness using dual electrode separation in the focused impedance method (FIM)

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Abstract

Subcutaneous fat layer thickness in the abdomen is a risk indicator of several diseases and disorders like diabetes and heart problems and could be used as a measure of fitness. Skinfold measurement using mechanical calipers is simple but prone to error. Ultrasound scanning techniques are yet to be established as accurate methods for this purpose. Magnetic resonance imaging (MRI) and computed tomography (CT) scans can provide the answer but are expensive and not available widely. Some initiatives were made earlier to use electrical impedance to this end, but had inadequacies. In the first part of this paper, a 4-electrode focused impedance method (FIM) with different electrode separations has been studied for its possible use in the determination of abdominal fat thickness in a localized region. For this, a saline phantom was designed to provide different electrode separations and different layers of resistive materials adjacent to the electrodes. The background saline simulated the internal organs having low impedance while the resistive layers simulated the subcutaneous fat. The plot of the measured impedance with electrode separation had different ‘slopes’ for different thicknesses of resistive layers, which offered a method to obtain an unknown thickness of subcutaneous fat layer. In the second part, measurements were performed on seven human subjects using two electrode separations. Fat layer thickness was measured using mechanical calipers. A plot of the above ‘slope’ against fat thickness could be fitted using a straight line with an $R^2$ of 0.93. Then this could be used as a calibration curve for the determination of unknown fat thickness. Further work using more accurate CT and MRI measurements would give a better calibration curve for practical use of this non-invasive and low-cost technique in abdominal fat thickness measurement.

Keywords: electrical impedance, electrical impedance tomography, focused impedance, abdominal fat thickness, obesity

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

Obesity has become a world-wide problem. Too much body fat is considered a serious health risk. Extra fat around the abdomen and waist is associated with a higher risk of diabetes, heart disease and hypertension (Wiklund et al 2008, International Diabetes Federation 2011). Therefore measurement of abdominal fat thickness would allow the early detection of such risks. Besides, it can also be used to indicate the fitness that a person has, or to monitor changes obtained through a fitness programme. Skinfold thickness measured using calipers is the simplest way of assessing subcutaneous fat layer thickness, but it suffers from inaccuracy. computed tomography (CT) and magnetic resonance imaging (MRI) are two methods by which we can measure abdominal fat thickness accurately, but these are very expensive and not available widely. Therefore, there is a need to develop a simple and low-cost method for the measurement of abdominal fat thickness.

Electrical impedance techniques offer a possible solution to the above requirement. These techniques are simple, easy to handle and use low-cost instruments. A group at the Technical University of Graz, Austria used an electrical impedance method known as tetrapolar impedance measurement (TPIM) to measure the impedance across the waist of a number of subjects and compared these with the thickness of subcutaneous fat layer measured using MRI and found a significant correlation ($r^2 = 0.99$) between them (Scharfetter et al 2001). In the traditional arrangement of TPIM, four electrodes are arranged in a line and current is driven between the outer pair of electrodes (source electrodes) and potential is measured between the inner pair (receive electrodes). This arrangement gives the bulk impedance eliminating the effects of contact impedance. However, TPIM has a wide zone of sensitivity between the receive electrodes; therefore, the measured impedance may include contribution of tissues other than the desired zone. The thickness of abdominal fat layer changes with location; therefore, TPIM measurement may only give an average at best, not a location wise distribution. Besides, a TPIM has considerable areas with negative sensitivity, which again depends on the arrangement of the electrodes (Rabbani et al 1999, Islam et al 2010). Since abdominal fat is extended over a large area, part of it will be in the zones with negative sensitivity contributing to a reduction in the impedance value. For this reason even though a good correlation was found by the Graz group, variation in electrode configuration may affect the results in a complex way. The measured values will also depend on the lateral extension of the subcutaneous fat layer.

In an earlier work our extended group studied a new concept for the determination of abdominal fat thickness (Haowlader et al 2010). They looked for ways to find the thickness by changing the electrode separation in TPIM. Since the current paths within the fat layer (with high resistivity) and those crossing the fat layer into the low resistive abdominal tissues behind will have distinctive patterns, the impedance measured is expected to change sharply when a major part of the current distribution crosses the fat layer and enters the bulk tissue underneath. It was thought that this should get reflected in the measured values with changing electrode separation. Measurements were performed on a saline phantom (dummy simulating the human body). Many electrodes were fixed in a straight line on a rigid polystyrene foam block at small separations and it was allowed to float on the top surface of the saline with the electrodes facing downwards, touching the saline surface. Conventional TPIM measurements were performed for different source and receive electrode separations. The same measurements were then repeated with different thicknesses of spongy plastic foam (soft polyurethane) immersed in the saline, pressed down using the rigid polystyrene foam block. Saline entered into the pores in this spongy foam to make its effective resistivity higher than that of saline, in effect making a layer of high resistivity material simulating subcutaneous fat in the human abdomen. The idea was to find a technique which could be used to determine the thickness of such layers...
by changing electrode separations of TPIM. It was found that for a fixed receive electrode separation, the measured impedance remains almost the same at low values of source to source electrode separation, but then the impedance falls sharply with increasing source to receive electrode separation, until saturating to a low value. It was also observed that the knee at which the impedance value starts to fall sharply, increases for increasing thickness of immersed foam layer. Therefore it was suggested that the position of this knee in terms of the source–electrode separation may give an assessment of the thickness of foam layer, which could be similarly translated to abdominal fat thickness. However, the source electrode separation was rather small at which the knee in the above plots occurred and there is a possibility of missing it for low thickness of the abdominal fat layer.

Following the partial success of the above work with TPIM, the present work was taken up to study the possibility of using a newer technique, known as the focused impedance method (FIM) developed by our extended group at the University of Dhaka, Bangladesh (Rabbani et al 1999, Rabbani and Karal 2008) with the same objective. FIM can focus a particular zone of interest bounded by the electrodes, and the negative sensitivity is also reduced compared to TPIM, in both magnitude and geometrical extension. Therefore, FIM may be useful in determining the fat thickness in a particular defined area. It needs to be mentioned that whether using TPIM or FIM, the measurement of fat thickness using surface electrodes is possible because of 3D sensitivity of these techniques. Therefore, an understanding of the 3D sensitivity and the effects of the electrode placements and their variations have to be understood properly in order to achieve success in this application.

There are three versions of FIM: one uses eight electrodes, another one uses six electrodes and the third, four electrodes. The present work uses the last version which is briefly described with the help of figure 1. Four electrodes 1, 2, 3 and 4 are placed at the corners of a square as shown in figure 1. An alternating current of constant amplitude $I_1$ is first passed between electrodes 1 and 2, and the potential $V_1$ is measured across electrodes 3 and 4. This is essentially a TPIM with a horizontal sensitive zone shown shaded between the equipotential lines passing through the receive electrodes 3 and 4, giving an impedance $Z_1$. Current $I_2$ is then passed between electrodes 2 and 3 and potential $V_2$ is measured across electrodes 1 and 4 with the corresponding vertical sensitive zone shown shaded between equipotential lines passing

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**Figure 1.** Basic concept of 4-electrode FIM.
through the receive electrodes 1 and 4, giving an impedance $Z_2$. This gives another TPIM measurement. The sum of the two impedance values $Z_1 + Z_2$ gives an enhanced sensitivity in the central dark shaded region bounded by the four electrodes (Rabbani and Karal 2008). The focused sensitivity has been verified using phantom experiments in this work, and through analytical simulation (Islam et al 2010).

Based on this FIM, measurements were carried out on a phantom with different electrode separations in order to find out a technique that could give the thickness of localized abdominal fat reliably.

2. Methods

The FIM essentially consists of two orthogonal TPIM measurements as mentioned above. Equipment made in our laboratory earlier for TPIM was used for the measurements in this study. This equipment provided an alternating current at a frequency of 10 kHz with constant amplitude of about 0.5 mA. Since the current is maintained constant, the measured potential is proportional to the impedance, and therefore the potential value can directly be used as a representative transfer impedance value.

First, a phantom was designed for the present study. It consisted of a saline-filled transparent plastic tank in which carbon electrodes were fixed at the bottom. Some resistive sheets (spongy plastic foam, raw cow-hide) were laid down at the bottom (figure 2). Through this arrangement the saline in the phantom simulated the muscle and other tissues with low resistivity in the human abdomen, and the resistive sheets simulated the subcutaneous fat layer.

The base of the tank had a square area of 12 cm × 12 cm. Twelve circular carbon electrodes of about 5 mm diameter were fixed at the corners of three concentric squares in the bottom as shown in figure 3. Electrical connections were taken out from below the tank. The sides of the squares were 3.5, 5.7 and 8.5 cm, respectively, which were also taken as the respective electrode separations for the measurements performed. An inner plastic frame, open both at the top and the bottom, and fitted with crossed plastic bars at the bottom was made to press the foam sheets in the saline from the top, to prevent the foams from floating (figure 4). The total height of saline in the tank, including resistive sheets was maintained at 6 cm for all the measurements as indicated in figure 2 through addition or subtraction of saline from the tank as necessary.

Raw cow hide and four types of plastic foam sheets of different thicknesses and (as available) were used for the resistive layers for the phantom, and these are described.
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Figure 3. Electrodes positions (indicated by black dots) on the bottom of the phantom.

![Electrodes positions](image1)

Figure 4. The phantom with an inner plastic frame with crossed thin bars at the bottom.

![Phantom structure](image2)

Table 1. Description of the plastic foam and raw hide used for the resistive layers.

<table>
<thead>
<tr>
<th>Type of the material (density)</th>
<th>Thickness (mm)</th>
<th>Maximum number of sheets used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-1 foam (26.68 × 10⁻³ g cm⁻³)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Type-2 foam (35.33 × 10⁻³ g cm⁻³)</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>Type-3 foam (26.47 × 10⁻³ g cm⁻³)</td>
<td>23.5</td>
<td>2</td>
</tr>
<tr>
<td>Type-4 foam (6.42 × 10⁻³ g cm⁻³)</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>Raw cow-hide</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>

in table 1. A plastic foam sheet is essentially a multitude of pores within an insulator. When a sheet of foam is immersed in the saline, it effectively forms a layer with a higher resistivity than that of the saline. The hide is also similar but it is dead animal tissue having a complex microscopic structure. The electrical impedance in this case is expected to have frequency dependence (Weir 1952). However, at a particular frequency of measurement, it will offer a fixed value of impedance. Being denser it will provide layers with higher values of impedivity.
compared to the values of resistivity of the spongy foam sheets. Before each measurement with saline with a particular concentration, all these sheets were kept immersed in the same saline for a few hours, more for the raw hides, to ensure that saline has entered the pores well.

At the beginning of the measurement, the tank was filled up with saline to a depth of 6 cm. The impedance of the saline phantom was measured by FIM using the three different electrode separations, in turns. These were considered as the background values of impedance. After this, a resistive sheet, cut to shape and already soaked in saline of the same concentration, was laid down at the bottom within the saline. It was pressed down lightly to the bottom using the inner frame described above. Care was taken with the foam sheets so that these were not compressed beyond that needed to keep them from floating. FIM measurements were again performed using the three sets of electrodes. More resistive sheets of the same type were added in turn on the top of the previous ones to give different effective thicknesses of the resistive layer, and the measurements taken as mentioned. As the height of saline increased due to the insertion of new sheets, saline was removed from the tank to keep the combined total height constant at 6 cm in each case. We repeated the above measurements changing the concentration of the saline as well. The concentration was varied by varying the amount of salt in water.

Next, measurements were made on live human subjects, all male but having different abdominal thicknesses. Electrode separations chosen were 4 cm and 6 cm. The focused zone was chosen just to the right of the navel, with the centre of the focused zone at the same horizontal line as the navel. The subjects lied down on a patient bed with chest up. The fat layer thickness was measured using mechanical calipers roughly around the centre of the focused zone.

### 3. Results and observations

For the phantom measurements, for each electrode separation all the measured impedances with resistive sheets were normalized to the corresponding impedances measured with the respective background saline only. For a particular concentration of saline and for a particular material, the normalized impedances were plotted against electrode separation, for different thicknesses of the material, as shown in figure 5 for cow-hide, and in figure 6 for type-1 foam.
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Figure 6. Normalized impedance (Z) versus electrode separation (S) for type-1 foam (saline conductivity: 0.72 mS).

Figure 7. Schematic diagram of current paths in saline-sheet system with different electrode separations. The actual current paths will be more complex but will have similar general form.

It can be seen that the impedance value decreases as the electrode separation is increased from 3.5 to 5.7 cm, and the change is very small beyond this. This behaviour may, in principle, be explained with the help of figure 7.

For a smaller electrode separation, a major portion of the current passes through the resistive sheets and a smaller portion passes through saline above. Therefore the impedance is high. For a larger electrode distance, the portion of the current passing through the resistive sheets is less. That means a greater portion of the current goes through the saline (the low resistance material), giving a lower impedance value. Hence, we have a general result: lower electrode distance gives higher impedance values. As the electrode separation is further increased, the portion of current passing through the background saline contributes more, and it becomes almost constant. Had it been a simple linear TPIM, increased electrode separation would have contributed to slightly increased impedance as the length of the effective sensitive zone increased. However, in FIM, it is the area of the focused zone that increases with electrode
separation, so the impedance value is expected to be almost unchanging with further increase in electrode separation.

A feature apparent from figure 5 seems to lead to a method for the determination of the thickness of the resistive layer. Between the electrode separations of 3.5 cm and 5.7 cm, the slopes of all the curves are not the same; they seem to have a systematic change. The absolute values of the slopes are plotted against the sheet thickness in figure 8. The same was plotted for the type-1 foam in figure 9 from the slopes of figure 6. The features are similar.

Figures 8 and 9 suggest a way of measuring the thickness of the resistive layer. These plots may be treated as calibration curves for the particular type of resistive materials, for the particular background saline concentrations.

The measured slopes (absolute value) of impedance for different abdominal fat layer thickness obtained from seven human male subjects are plotted and shown in figure 10.
Abdominal fat thickness using focused impedance method

y = 111.76x - 73.818
R² = 0.9343

Figure 10. FIM values for abdominal fat thickness, measured using calipers, of male subjects.

4. Discussion

Measurement of abdominal fat thickness seems to be important from the point of view of preventive care. Since abdominal fat is a risk indicator of a number of diseases and disorders, a low-cost and simple device for its accurate measurement will be a useful addition in medicine, particularly for screening of patients. It would be also useful for monitoring fitness of normal healthy people, or in monitoring the results of any fitness programme. Of course internal visceral fat in the abdominal region is also a risk parameter; however, the present work concentrates on the subcutaneous fat layer, which in itself is important for the above applications.

TPIM and FIM methods both seem to be capable of measuring subcutaneous fat layer in some way. However, just the direct impedance value as suggested by the Graz group may not work in every subject since the absolute value of abdominal impedance will depend on the size and shape of the person. Besides, TPIM measured using a line of electrodes across the waist will have contribution from both upper and lower regions which may include regions other than the abdomen. Again, even within the abdomen the thickness of the subcutaneous fat layer is not the same throughout. Therefore, FIM appears to be a better choice since it can be used to localize the zone of study within an approximate square area with sides of a few cm.

The skin layer coming between the electrodes and the fat layer will contribute to the measurement. A simplifying assumption that it is the same for all subjects may be taken at this preliminary stage of the study. Moreover, since the average sensitivity of the FIM is low near the electrode surface and is maximum at a depth of about one third the electrode separation (Islam et al 2010), the contribution of the skin layer will be reduced, and the above assumption may be acceptable.

It can be seen from figures 8 and 9 that the measured data points for the raw cow-hide matched the fitted curve very well while it was not so for the sponge. Working with spongy foam sheets was a bit tricky since these tend to float creating pockets filled with just saline,
particularly when multiple layers are introduced. Putting pressure through the inner frame could compress the sponge along the edges of the frame and along the cross bars in the middle, increasing the resistivity at these points. On the other hand raw cow-hide did not have such sponginess. This may explain the quality of matching to the fitted curves observed.

The pores in the hide are very small and therefore these needed to be soaked for several hours in saline of a concentration that would be used in the measurements in the phantom. Otherwise, if the hide retains some saline with other concentrations, or remains dry at points, these will contribute to a dynamic process of diffusion during the measurement, contributing to variations in the results, and errors. Again, a solid insulating material like plastic could not be used since it would not allow any current to pass, and therefore, no dependence on thickness could be observed.

The graph obtained from measurements on human subjects as shown in figure 10 indicates the potential for success of the present method in the measurement of subcutaneous fat thickness. This plot may be used as a calibration curve. However, the results should be supplemented by measurements on a large number of subjects. From an intuitive standpoint it should be done separately for males and females since the fat accumulation patterns are usually different. Fat thickness measured using mechanical calipers is subject to error as the pressure applied to a skinfold may vary from reading to reading, and the compliance to pressure may be different for different fat thicknesses. This may be the reason for the deviations of the measured points from the fitted straight line in figure 10. Besides, one needs to be careful in selecting the point in the abdomen where the fat thickness is measured using the calipers since the thickness varies with position as well. This will also contribute to an error. It would be better to use CT or MRI to measure the fat thickness at a specific point, preferably coinciding with the centre of the focused zone of impedance measurement, to make the calibration curve more accurate and reliable. In this work the fat thickness was measured on the right side of the navel using only two electrode separations of 4 cm and 6 cm. The position on the abdomen, and the electrode separation, both are important from a point of view of standardization, and should be specified.

That the slope of the curve of impedance versus electrode separation could be used to develop a technique for subcutaneous fat layer thickness was visualized intuitively during an earlier work in our laboratory using TPIM (Haowlader et al 2010) on phantoms. During analysis of this work, apparent changes in the position of knees were noted in a curve of measured impedance against current-to-current electrode separation for different thicknesses of simulated fat layers. The slopes also apparently changed somewhat, but it was not appreciated at that time. In the present study with FIM, this slope has become the method of choice.

In the above work it is assumed that the impedivity of subcutaneous abdominal fat and that of the background muscle and other tissues will be the same for all people. This may not strictly be true; however, further studies incorporating variations in such structures are expected to give further information which would allow minimizing the effects. RF field mapping of MRI scans may provide information about the type of the tissue and its electrical properties in subcutaneous abdominal fat and that of the background muscle (Zhang et al 2010). Furthermore, age, weight and BMI specific calibration curves may be obtained to reduce the subject-specific errors. Again visceral fat in organs behind the subcutaneous fat layer may contribute to the results; however, because of reduced sensitivity with depth, this may not be significant.

The present work is just a preliminary work to show the feasibility of using FIM with more than one electrode separation in measuring subcutaneous fat thickness, and the calipers method was chosen for comparing the results in view of its simplicity. The next phase of work
should concentrate on the accuracy of this measurement. For this work, the possible techniques for comparison are ultrasound scan (A-scan or B-scan), CT and MRI.

Using ultrasound, measurement of the thickness of subcutaneous fat layer is possible because of the echo coming from the interfaces between skin and fat, and between fat and lean tissue, due to their different acoustic impedances (Booth et al 1966, Wilkinson and Mcewan 1991). However, the ultrasound method suffers from a phase aberration problem arising from the distortion of wave-fronts due to different acoustic velocities in different media (Abrahim et al 2007). Several methods have been proposed to address this problem but they are quite complex (Ng 2006). Comparative studies have been performed between measurements of subcutaneous body fat thickness using skinfold measurement and ultrasound methods, and evaluated using CT. The ultrasound method has been found to be superior to the skinfold measurement method in some studies (Black et al 1988) and less accurate in others (Orphanidou et al 1994). It seems that the ultrasound method is not yet well established as a measure for subcutaneous fat thickness. Therefore, in order to establish FIM as a new technique for such measurements, the systems of choice for comparison should be either CT or MRI.

FIM offers localized measurement of impedance using very simple instrumentation, and its potential in various clinical diagnosis and physiological studies are coming up through research and development carried out at Dhaka University and in a few other laboratories around the world. Measurement of the thickness of subcutaneous fat layer is an attractive application of FIM, and measurement using two electrode separations as suggested through this work, may become a tool of primary choice for this application.

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References


Ng J Y C 2006 Automatic measurement of human subcutaneous fat with ultrasound MA Sc Thesis Department of Electrical and Computer Engineering, University of British Columbia, Canada (Available at http://circle.ubc.ca/handle/2429/18632)


Wilkinson M J A and Mcewan N A 1991 Use of ultrasound in the measurement of subcutaneous fat and prediction of total body fat in dogs *J. Nutr.* **121** S47–50 (Available at http://jn.nutrition.org/content/121/11_Suppl/S47.full.pdf+html)