Abdominal fat thickness measurement using Focused Impedance Method (FIM) - phantom study

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Abstract. Abdominal fat thickness is a risk indicator of heart diseases, diabetes, etc., and its measurement is therefore important from the point of view of preventive care. Tetrapolar electrical impedance measurements (TPIM) could offer a simple and low cost alternative for such measurement compared to conventional techniques using CT scan and MRI, and has been tried by different groups. Focused Impedance Method (FIM) appears attractive as it can give localised information. An intuitive physical model was developed and experimental work was performed on a phantom designed to simulate abdominal subcutaneous fat layer in a body. TPIM measurements were performed with varying electrode separations. For small separations of current and potential electrodes, the measured impedance changed little, but started to decrease sharply beyond a certain separation, eventually diminishing gradually to negligible values. The finding could be explained using the intuitive physical model and gives an important practical information. TPIM and FIM may be useful for measurement of SFL thickness only if the electrode separations are within a certain specific range, and will fail to give reliable results if beyond this range. Further work, both analytical and experimental, are needed to establish this technique on a sound footing.

1. Introduction
Abdominal fat consisting of both subcutaneous (under the skin) and visceral (around deeper organs) fat have been found to have a bearing on health conditions, and are being used as risk indicators, particularly for Cardiovascular disease and Diabetes [1][2]. Existing reliable and direct methods for measuring fat thickness are MRI and CT scans, which are expensive, and are not available widely. Therefore there is a necessity of a direct measurement method that is reliable and widely usable.

Electrical impedance techniques offer a possible solution and there has been several efforts in this direction [3]. Some of these measure the impedance of the whole thorax while some use localised tetrapolar impedance measurements (TPIM) at the abdomen. The latter is particularly suitable for the subcutaneous fat layer (SFL) and this paper also concentrates on this measurement. However, even a TPIM system has a wide zone of sensitivity and it seemed logical to try the application of a recently developed technique known as Focused Impedance Method (FIM), innovated by our group at Dhaka University[4][5], which may provide an improved performance. One version, known as the 6-electrode FIM, is to be used for this study, which essentially is two orthogonal TPIM systems placed centrally over a common zone, which is the resulting focused zone of interest. FIM therefore shares many inherent features of TPIM. Therefore, the main focus of the present work was in developing some insight and understanding of TPIM towards measurement of abdominal fat, particularly of the
SFL. The distance between various electrodes in TPIM may have a bearing on the measured value of SFL thickness, therefore it seemed justified to study this aspect first, using TPIM in a phantom. The target is to get an optimum electrode separation for TPIM which could then be applied to FIM. As the distance between the current drive electrodes in a TPIM increase, the current density distribution spreads out and it is expected that the depth sensitivity will increase too. Therefore, an objective of this work was also to see if any new technique can be found out for measuring SFL thickness by changing the electrode separations.

2. Methods and Models

Schematic of the phantom designed and developed for this work is shown in figure 1. Electrodes were fixed into a plastic (polystyrene) foam piece floating on saline in a square tank made of transparent acrylic (PERSPEX) measuring 50cm x 50cm in area having a saline depth of 50cm as well. The lower side of the electrodes touched the saline while connections were taken out from the top. To simulate subcutaneous fat layer, one or more layers of plastic sponge were immersed into the saline at the top and then pushed down using the polystyrene foam piece, with appropriate weights placed on the top. The electrode at the centre served as the common terminal for a differential potential measuring arrangement. Symmetrically from the centre, two proximal electrodes were chosen for potential measurement, and two outer ones for current drive (source), to configure a TPIM arrangement. This gave a number of source to source (S-S) electrode and potential to potential (P-P) electrode separations. Current at 10 kHz was used for the measurement, and both current and voltage amplitudes were measured to provide an impedance value. Measurements were carried out for different P-P and S-S separations and for different thickness of the plastic sponge layer. To vary the thickness of the sponge layer, additional sponge pieces were introduced by taking the polystyrene foam sheet out and replacing it again.

The effect of increasing the S-S separation is discussed using a simple intuitive model as shown in figure 2. Suppose the P-P separation (PQ) is kept fixed, while the S-S separation is changed (CD to AB). Because of the spread of current lines the depth sensitivity is expected to be higher for the wider current drive AB than for drive CD, as schematically represented by the approximate semicircular current lines. Therefore the impedance measured with drive CD is that of the region PLMQ with current driven perpendicular to PL and QM, denoted by Z₁. For current drive AB, the impedance Z_p measured is that of the region PNOQ with current driven perpendicular to PN and QO, which can be modelled as a parallel combination of Z₁ and Z₂, where Z₂ is the corresponding impedance of the region LMON, again perpendicular to the current direction. Therefore the value of this combined impedance would be less than Z₁. For a volume conductor the incremental sensitive volume is large and is expected to contribute to a significant reduction in the measured impedance. Thus with increased S-S separation the measured impedance is expected to decrease.
However, in the above description, the negative effect of the impedance ($Z_{N1} + Z_{N2}$) of the zones between the current and potential electrodes has not been considered. In TPIM measurements a significant negative sensitivity has been observed in these zones [4], and needs to be considered in the present case. If an insulator is placed in the central zone within the saline, between electrodes P & Q in figure 2, the bending of equipotentials will give rise to a higher potential difference between P & Q, resulting in increased measured impedance, compared to the background measured impedance due to saline only. On the other hand if an insulator is placed between the source electrode C and the potential electrode P, then the resulting measured impedance will decrease because of reversed bending of equipotential lines. This gives rise to the negative sensitivity. In the present situation, either for the saline alone, or for sponge layers soaked in saline at the top, the impedance is distributed throughout the region of the electrodes. Therefore, the impedance $Z_{N1} + Z_{N2}$ contributes to a reduction in the measured impedance as $Z = Z_P - (Z_{N1} + Z_{N2})$. As can be visualised from figure 2, for an increase in the source to potential electrode separation (S-P separation), the impedance $Z_{N1} + Z_{N2}$ is likely to increase, while due to an increase in the depth sensitivity, this is likely to decrease. So the combined effect would be complex and is likely to vary for different S-P separations. The results of the experiments performed on the phantom are given in the next section.

3. Results and Observations
Figure 3 shows the impedance values as a function of S-S separation for fixed P-P separations of 2 cm, and for two different thickness of the sponge layer (3.5cm and 7.5cm) and one with no sponge (or zero sponge thickness). It can be seen that the impedance increases with increasing thickness of sponge, which is reasonable to expect, and which has been used by other workers [3]. However, the steep slope of fall of the impedance with increasing S-S separation means that small changes in electrode positioning could lead to significant changes in the impedance values. This naturally suggests that TPIM measurement will give different impedance values for the same abdominal SFL thickness for slightly different P-P and S-S separations, and therefore give unreliable results in practice. However, when the phantom experiment was performed for increased values of P-P separation, a horizontal segment began appearing in the beginning of the curves. Figure 4 shows the results for a P-P separation of 4 cm. At this value a horizontal segment was noticeable even without any sponge layer at the top, while larger horizontal segments were visible for increasing sponge layer thicknesses. This new finding seems to provide a usable range within which a small variation in electrode placement may not change the measured impedance value significantly, and may therefore provide a reliable measurement favouring the use of a TPIM system for abdominal SFL thickness.

The reason for the generation of the horizontal segment is not very straightforward and a possible explanation is provided in the next section. However, the above results suggest that the ratio of S-S to P-P separation is to be kept within a certain range if TPIM or FIM are to be useful for measuring SFL.

![Figure 3. Variation of impedance with S-S separation for a P-P separation of 2 cm. Sponge thickness: 0 (no sponge), 3.5cm, 7.5cm](image1)

![Figure 3. Variation of impedance with S-S separation for a P-P separation of 4 cm. Sponge thickness: 0 (no sponge), 3.5cm, 7.5cm](image2)
thickness. From figure 4 it appears that for the phantom used, a maximum S-S separation of 8 cm may be used, corresponding to a maximum S-S/P-P ratio of 2. Of course, for abdominal fat measurement, a proper figure of this ratio has to be obtained through further studies on more realistic phantoms having close values of impedances and for practical ranges of SFL thickness.

Another point worth noting are the values of S-S to P-P ratio at the knees of the curves for the different sponge thicknesses in figure 4, which seem to be increasing with increasing sponge thicknesses. Therefore, such values at knee may be utilised to extract a value of the SFL thickness, however, further studies would be necessary to make it a practicable technique.

4. Discussions
This study gives an important insight into the use of TPIM, and of FIM for studies of abdominal SFL thickness. Since the SFL is spread in three dimensions, it contributes to the measured impedance in a complex way, having both positive sensitivity in the central region between the potential electrodes, and negative sensitivity outside. This work has presented an intuitive physical model based on current density distribution and perturbation of equipotential surfaces, using which a qualitative prediction was made for decreasing impedance with increasing S-S separation. The prediction was borne out by measurements on a phantom having saline and saline soaked plastic sponge layers. However, the measurements produced a new finding, almost unchanging impedance at low values of S-S separation. This was beneficial and important since this gives the possibility of absolute impedance measurement in order to obtain SFL thickness reliably by choosing appropriate P-P and S-S separations. This observation may be explained, again using the negative and positive sensitivity regions mentioned above. At low values of S-P separation the impedance \( Z_{N1} + Z_{N2} \) to be subtracted is small in comparison to \( Z_P \), however, as S-P separation increases, \( Z_{N1} + Z_{N2} \) is no longer insignificant, and eventually dominates resulting in the very small measured impedance. This phenomenon is not frequently discussed as mostly the target is considered to be localised within the central sensitive volume. However, this negative sensitivity is present in any TPIM measurement, and artefacts with negative sensitivity observed in EIT images are in fact due to this phenomenon. Further work, including an analytical treatment is needed in this direction which will establish both TPIM and FIM techniques on a sound footing.

5. References

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