IMPEDANCE MEASUREMENT USING THE FOUR ELECTRODE TECHNIQUE

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Abstract

This work explores the effect of non-uniform current density between electrodes when measuring impedance using the four electrode (tetrapolar) technique in saline and blood. The analytical solution for the electric potential inside an infinitely long, square cross section isotropic conductor from a point current source and sink in the centre, separated by an arbitrary distance, is presented. Experimentally measured potential differences using the four electrode technique inside long square cross section tubes filled with blood and saline agreed to a few percent of the theory. The work was primarily undertaken to validate experimental technique for use in impedance measurement experiments in sheep. The authors are interested in the use of this method to determine right ventricular volume in the heart.

Key Words

Biosensors and transducers, impedance measurement, four electrode technique, conductance catheter.

1. Introduction

We are interested in the effects of non-uniform current density when using the four electrode (tetrapolar) technique and, in particular, when using the technique for estimating blood volume in the right ventricle of the heart. Here we investigate relevant aspects of the use of this technique. Our approach involved measuring the electric field inside a long conductor of square cross section, using a conducting solution of either saline or blood, and then comparing this to an analytical solution for the field. Outcomes included the validation of our experimental technique in taking impedance measurements, an experimental investigation of the electric field within the conductor and evaluation of the conductance of blood used in the experiments.

Factors affecting the conductance of saline and blood were important considerations. Saline conductance can be calculated using published data [1] and is found to vary significantly with temperature and concentration. Blood is a much more complicated solution and its conductivity varies [2,3,4] with many parameters such as hematocrit and velocity (due to orientation of blood cells).

Impedance methods are regularly used to measure cardiac properties such as ventricular volume [5,6,7]. Methods often assume a uniform electric field in the vicinity of the heart. We are interested in taking these measurements with a non-uniform field generated by relatively closely-spaced electrodes within the ventricle. Part of this work will involve taking impedance measurements within sheep using the techniques investigated here.

2. Theory

The analytical solution for the electric potential inside an infinitely long, square cross section isotropic conductor containing a point current source and sink (electrodes) along the centre line as in Figure 2.1 was developed from first principles.

Let \( \sigma \) = conductivity of conductor and \( I_0 \) = current source/sink magnitude or electrode current. If the potential at the origin of the \( x, y, z \) axis is zero, then the

![Figure 2.1](image_url)
electric potential $V$ in the conductor can be shown to be given by,

$$V = \frac{l_1 L}{2 \sigma D}$$

$$+ \sum_{n=0}^{\infty} \frac{l_n}{D} \cos \left( \frac{2 \pi}{D} \right) \left( e^{\frac{2 \pi}{D} x} - e^{-\frac{2 \pi}{D} x} \right)$$

for $z < -\frac{L}{2}$,

$$V = \frac{l_z L}{2 \sigma D}$$

$$+ \sum_{n=0}^{\infty} \frac{l_n}{D} \cos \left( \frac{2 \pi}{D} \right) \left( e^{\frac{2 \pi}{D} x} - e^{-\frac{2 \pi}{D} x} \right)$$

for $-\frac{L}{2} < z < \frac{L}{2}$ and

$$V = \frac{l_1 L}{2 \sigma D}$$

$$+ \sum_{n=0}^{\infty} \frac{l_n}{D} \cos \left( \frac{2 \pi}{D} \right) \left( e^{\frac{2 \pi}{D} x} - e^{-\frac{2 \pi}{D} x} \right)$$

for $z > \frac{L}{2}$.

The solution is shown visually in Figure 2.2.

3. Experimental Method

The electric field was explored experimentally inside closed, long, square cross section Perspex tubes filled with saline and with blood. A 100mmx100mmx550mm tube and a 43mmx43mmx550mm tube were used for experiments in saline. The 100mm wide tube and associated electrode setup are shown in Figure 3.1 and Figure 3.2 respectively. A 50mmx50mmx250mm tube was used for experiments in blood. Electrodes were aluminium or brass rods coated with heatshrink plastic.

The theory suggests the electric potential becomes relatively constant not far (in the order of the tube width) past the current source and sink from the origin. Therefore it should be expected that the electric potential between the current source and sink is not much different in a finite length conductor that extends just (in the order of the tube width) past the source and sink, than in an infinitely long conductor.

A bipolar $\pm 500\mu A$ current at 100Hz was supplied between two source electrodes. The electric potential between another two electrodes (measurement electrodes) was measured at various source and measurement electrode positions along the centreline of the tubes. Essentially no current was drawn by the measurement electrodes. Therefore essentially no electrode polarisation would occur at these electrodes. Measurements of electric potential were made using a digital oscilloscope. Oscilloscope waveforms were uploaded to a computer and analysed using the oscilloscope software.

For the saline experiments the tubes were filled with distilled water containing a measured quantity (0.5000g) of NaCl so that the conductivity of the solution could be calculated from chemical literature. For the blood experiments the conductivity was determined by fitting the theory so that the mean error of the results was zero. (Thus from the blood experiments only the relative shape of the electric field in the tube could be determined.)

Experiments were conducted for three different source electrode spacings (103mm, 203mm and 303mm between
the middle of the exposed part of the electrodes, \(L\) in the 100mm\(\times\)100mm\(\times\)550mm tube and one source electrode spacing (\(L = 303\)mm) in the 43mm\(\times\)43mm\(\times\)550mm tube with saline. Three different source electrode spacings (75mm, 105mm and 150mm) were used in the 50mm\(\times\)50mm\(\times\)250mm tube with sheep blood. In each test the waveform between measurement electrodes at various spacings \(L'\) up to the source electrode spacing were recorded and analysed. The source electrodes and the measurement electrodes were symmetrically located in the tubes.

The distance between centre lines of the measurement and source electrodes in the tubes used for saline tests was 5mm. This was accounted for in the theory by assuming that the source electrodes were in the centre of the cross section and the measurement electrodes were located 5mm off-centre.

4. Results

This section presents experimental results and corresponding theoretical results. Results for the various tests conducted in saline are shown in Figures 4.1 and 4.2. The results for the tests conducted in sheep blood are shown in Figure 4.3. Notation is the same as that used previously. \(L = \) distance between source electrodes. \(L' = \) distance between measurement electrodes (which were symmetrically located between the source electrodes.) The figures show non dimensional electric potential plotted against measurement electrode separation.

![Figure 4.1 Non-Dimensional Experimental (Cross) and Theoretical (Line) Results for Saline in 100mm\(\times\)100mm\(\times\)550mm Tube (From Top to Bottom: \(L = 103\)mm, \(L = 203\)mm, \(L = 303\)mm)](image)

![Figure 4.2 Non-Dimensional Experimental (Cross) and Theoretical (Line) Results for Saline in 43mm\(\times\)43mm\(\times\)550mm Tube with \(L = 303\)mm)](image)
The fitted value of resistivity of the sheep blood was 113 Ω·cm (blood was at 24.9°C).

5. Discussion

Results in figures 4.1 and 4.3 are distinctly non-linear because measurement electrodes enter regions of high potential gradients near source electrodes. Figure 4.2 appears more linear because of large source electrode separation relative to tube width.

Overall there was excellent agreement between experimental and analytical results. The measured electric potential agreed to a few percent of the theory. The difference between experimental and theoretical results could be attributed to the experimental technique. This was assessed by sensitivity analysis using the theory, for the various parameters.

The experimentally derived value for blood resistivity is within the range of published values. Exact values depend on the experimental conditions.

Possible extensions to this work include exploring different geometries. Offsetting the source electrodes from the centre would require relatively simple modification of the theory presented (would require incorporating sine terms in the solution in addition to cosine terms). Complex geometries could be explored numerically using finite element software. The work would potentially be useful for anyone measuring the impedance of blood, tissue and ionic solutions. The good agreement between experiments and theory show the suitability of our techniques for measuring the electric field and impedance.

6. Conclusion

This work successfully explored the effect of non-uniform current distribution on impedance measurement using the four electrode technique in long, square cross section volumes of saline and blood. The experimental results agreed to a few percent of the theory. Possible extensions to this work include exploring different geometries. Offseting the source electrodes from the centre would require relatively simple modification of the theory presented (would require incorporating sine terms in the solution). Complex geometries could be explored numerically using finite element software. The work would potentially be useful for anyone measuring the impedance of blood, tissue and ionic solutions. The good agreement between experiments and theory show the suitability of our techniques for measuring the electric field and impedance.

References