Investigation of tissue bioimpedance using a macro-needle with a potential application in determination of needle-to-nerve proximity

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Abstract — Our research is concentrated on development of a ‘smart’ needle which will improve the safety of ultrasound-guided peripheral nerve block (USgPNB) by providing the clinician with bioimpedance data to identify the type of tissue the needle tip is in contact with. This paper outlines a feasibility study performed to determine the electrical bioimpedance of a number of different tissue types and the extent to which they can be differentiated from each other based on this variable factor. All cells have different electrical properties which results in characteristic bioimpedance profiles. A macro-needle was constructed to facilitate determination of this trait in lamb, pork and beef tissue samples. Frequencies of between 10 kHz - 100 kHz were identified as the optimum range for measurement of samples at both 12 °C and 37 °C. Our study showed that bioimpedance was inversely proportional to temperature. Further investigations in muscle, fat and connective tissue were performed at 30 kHz, 50 kHz and 70 kHz demonstrating significant order of magnitude of separation between all three sample types. These results allowed the determination of bioimpedance ranges for each tissue. The possibility of using bioimpedance to differentiate between tissue types was demonstrated successfully during this study and thus supports the concept of the ‘smart’ needle for this application.

Keywords - bioimpedance, peripheral nerve block, needle guidance

I. INTRODUCTION

USgPNB refers to a set of medical procedures which facilitate surgical operations or are performed to treat acute or chronic pain. It entails identification of specific nerves or plexuses, direction of a needle transcutaneously to these targets and injection of local anaesthetic. The entire procedure is visualised in real-time by ultrasound imaging. Administration of anesthetic to the target site results in selective and reversible interruption in sensory and motor nerve function. The needle tip position relative to the target nerve is crucial to the safe effective practice of USgPNB: if the needle tip is too close (i.e. within the nerve covering or epineurium), transient or permanent nerve injury can result; if it is too far away the block will be ineffective; if it punctures an adjacent structure (e.g vessel) life threatening complications can result. Over the past 8-10 years, ultrasound guidance for USgPNB has been more widely practiced. This poses two important problems: i) it is not possible to identify epineurium (and thereby minimize the risk of harmful intraneural injection) using ultrasound and ii) limits to the tools and resources available for effective training of a global population of anaesthetists in a new procedure.

It is possible to identify specific tissues and tissue interfaces based on characteristic and complex electrical impedance. Bioimpedance data can provide information on tissue type, location, (ultra)structure and function. Bioimpedance measurements have been used to provide tissue selective detection of tumors [1, 2], mammary glands and, crucially for this application, subcutaneous tissues [3]. However bioimpedance measurements in these studies were conducted using electrode systems with the counter electrode placed outside the body on the skin. This electrode configuration introduces bioimpedance from sources other than the tissue of interest. The novelty of our work relies on the design of a two electrode system which will be placed on the needle tip allowing for invasive bioimpedance measurement only at the needle tip. It is hoped this approach will increase the sensitivity and allow for accurate determination of tissue type during real-time needle penetration through the body. Addition of bioimpedimetric tissue identification in the form of the ‘smart’ needle to the current gold standard ultrasound imaging technique could be a solution to the aforementioned problems of USgPNB. To test if bioimpedance is a feasible characteristic to practically differentiate between tissue types invasively a pilot study was conducted in vitro using a two electrode needle system similar in design to the ‘smart’ needle. This study is detailed herein.

II. METHODS

A. Construction of the Macro-needle

The macro-needle was constructed (fig. 1) to measure bioimpedance of tissue at the needle tip in a similar fashion to how the ‘smart’ needle will operate but at a slightly larger
Two commercially available insulated needles (Stimpulex A, B Braun) with conductive tips were fixed together in a two electrode system. This macro-needle was connected to an impedance analyser (Zahner IM6).

**B. Frequency Sweep**

To determine the optimum frequency range at which the largest magnitude of separation between tissue types occurs, a frequency sweep was performed. The impedance analyser was set to measure impedance over 100 Hz – 1MHz recording impedance at 2 second intervals. Once the macro-needle was inserted into tissue, bioimpedance was recorded. The same tissue was analysed twice more before repeating the frequency sweep for the next tissue type. Pork, lamb and beef tissue samples, locally sourced from a butcher, were used and tested at two temperatures, 12°C and 37°C. Bioimpedance of muscle, fat and connective tissue was obtained. The results were graphically represented as a line graph bioimpedance (ohms) vs. frequency (Hz). The optimum frequency range for tissue differentiation was determined from these graphs (10 – 100 kHz).

**C. Time Analysis**

To investigate if bioimpedance of tissue samples remained constant over time, time analysis was performed. The impedance analyser was set to measure bioimpedance for 1 minute at a set frequency within the optimum frequency range identified above. The frequencies selected for the time analysis were 30, 50 and 70 kHz. This analysis was replicated 3 times for each tissue and the experiment was repeated 5 times. Once the macro-needle was inserted into the test tissue the bioimpedance was recorded. The results were graphically represented on a line graph.

**III. RESULTS**

**A. Frequency Sweep**

In the 5 analyses of the frequency sweep on the different tissue types in pork, lamb and beef higher bioimpedance was observed at low frequencies then those at higher frequencies. As the frequency was increased the bioimpedance decreased and plateaued between 10 and 100 kHz. Fat tissue in all meats and in all analyses had consistently higher bioimpedance than muscle. Bioimpedance values between those for fat and muscle were obtained for “border” tissue, (tissue observed between the fat and muscle mostly analysed in pork and lamb) and connective tissue mostly analysed in beef. The same trend was observed when the frequency sweep was repeated at 37 °C. The absolute bioimpedance values for each tissue type at 37 °C was lower than those recorded at 12 °C however the difference between fat and muscle bioimpedances at 37 °C was substantial and remained easily differentiated from each other. The results obtained during the frequency sweeps at 12 °C and 37 °C for pork follow (fig. 2) and represent the trends of all five analysis repeats. The results for lamb and beef demonstrated slightly higher bioimpedance but the trend remained the same with clear bioimpedance differences emerging between different tissue types, mainly fat and muscle. With the results illustrated on graphs like fig. 2 for all analyses undertaken at both 12 °C and 37 °C, it was identified that a frequency in the range of 10 – 100 kHz should be used to obtain bioimpedance values for the different tissue types in the different meats. To demonstrate that frequencies within this range were the optimum frequencies for further tissue bioimpedance investigation, the average bioimpedance values obtained at 10, 30, 50 and 70 kHz during the frequency sweeps for each tissue type on each meat were calculated. Fig. 3 shows substantial bioimpedance separation between the different tissue types of lamb using this frequency range, at both temperatures. This trend was also reflected for pork and beef.

**Figure 1:** A schematic of the macro-needle

**Figure 2:** Typical results obtained from a frequency sweep at both 12 °C and 37 °C. Note optimum tissue type separation between 10 and 100 kHz
B. Time Analysis

1) 12°C

Bioimpedance of different tissue types at 12 °C plotted against set frequencies demonstrated a straight line giving exact impedance for that tissue type with the exception of some fat measurements. These exceptions were lamb fat, which in all analyses, bioimpedance increased slightly over time. However at 70 kHz the increase of bioimpedance over time was small obtaining almost constant impedance. Bioimpedance recorded by time analysis showed distinct differences between tissue types. The median bioimpedance value was calculated for each tissue at 30, 50 and 70 kHz and these values (n=5) were used to calculate the average bioimpedance of each tissue type at each frequency. The approximate bioimpedance range for muscle, independent of species, was 100-175Ω. The approximate bioimpedance range of fat over the 3 meat types was 627 Ω - 3.2 kΩ and the range for border tissue was 221-540Ω.

2) 37°C

Bioimpedance of different tissue types was found to be reduced at the higher temperature of 37 °C. When bioimpedance was plotted against time, the graphs of each repeated experiment demonstrated constant bioimpedance (straight line) at 30 kHz. However when measuring at higher frequencies, 50 and 70 kHz, fluctuations of bioimpedance in fat tissue were observed. Despite these fluctuations the separation between tissue types still remained clear. Fig. 5 demonstrates what was observed. The median bioimpedance values were obtained for each tissue at 30, 50 and 70 kHz and these values (n=4) were used to calculate the average bioimpedance of each tissue type at each frequency. The approximate bioimpedance range for muscle, independent of species, was 100-175Ω. The approximate bioimpedance range of fat over the 3 meat types was 627 Ω - 3.2 kΩ and the range for border tissue was 221-540Ω.
IV. DISCUSSION

A. Frequency Sweep

Frequency sweeps over the range 100 – 1 MHz was selected after a literature review [4, 5]. This frequency range was wide enough to observe a trend and made it possible to identify a narrower frequency range at which tissue bioimpedance differed mostly for different tissue types. Analysis using the frequency sweep was initially performed at 12 °C. The frequency sweeps were repeated at 37 °C as this is body temperature and eventually on fabrication of the ‘smart’ needle, its application will be to deliver peripheral nerve blocks for regional anaesthesia in the human body. Bioimpedance data of different tissue types at 37 °C, therefore, will be required.

The following observations were made from the results of the frequency sweeps:

1. Muscle had much lower bioimpedance than fat. This was expected as other studies have noted muscle as a good conductor in comparison to fat, a good insulator [6].

2. Higher bioimpedance was observed at low frequencies than that at higher frequencies. This phenomenon is due to the membrane of the cell impeding current flow at low frequencies thus the current does not reach the intracellular fluid (ICF) of the cell. However at high frequencies the cell acts as a capacitor conducting current from the extracellular fluid (ECF) through the cell membrane (via ion channels) into the ICF [7]. The magnitude of bioimpedance of the cell under high frequency current is dependent on the tissue and the constituents of the ICF and ECF [8].

3. The narrower frequency range of 10 – 100 kHz gave the greatest separation of bioimpedance between different tissue types while also being the frequency range at which tissue bioimpedances were at their most constant value. This observation is supported by the findings of two published studies using bioimpedance to differentiate tissue type, [4, 5]. Subsequently the average bioimpedances of the different tissue types in the different meats at 10, 30, 50 and 70 kHz demonstrated clear separation between fat, muscle and border bioimpedance confirming this was the frequency range that should be used for further investigations.

4. Results from analysis at 37 °C demonstrated similar trends to those at 12 °C but at lower bioimpedances. An explanation for this is tissue composition changes with temperature and thus bioimpedance of tissues are altered at different temperatures. This demonstrates that bioimpedance is temperature dependent, also concluded by Geddes et al. with the statement “nearly all tissues exhibit a negative temperature coefficient of resistivity, i.e. the conductivity increases with increasing temperature” [9] supporting the need for analysis at 37 °C if this is the temperature at which this application is to be used.

B. Time Analysis

1) 12 °C

The first observation made from time analysis of different tissues in the 3 meats was that all tissues tested achieved constant bioimpedance (straight line) over the duration each measurement when bioimpedance was plotted against time, with the exception of lamb fat. Lamb fat bioimpedance increased over time at 30, 50 and to a lesser extent at 70 kHz. This gave an indication that bioimpedance analysis at 12 °C should be performed at 70 kHz. In summery the following observations were made:

1. Approximate ranges are useful and can differentiate between tissue type regardless of species and frequency, once within the 30 – 70 kHz.

2. Lamb, pork and beef present different bioimpedance for the same tissue types i.e. bioimpedance varies with species.

3. Beef had the lowest bioimpedance for each tissue when compared to lamb and pork, in fact beef tissue bioimpedance was consistently approximately half that of lamb tissue bioimpedance. Lamb had the highest bioimpedance of the 3 species for muscle while pork fat demonstrated the highest bioimpedance of the 3 species.

2) 37 °C

The results obtained during the time analysis at 37 °C presented significant SD of bioimpedance from the median over time for fat at 50 and 70 kHz. Constant bioimpedance or bioimpedance with low SD from the median was recorded at 30 kHz for all tissues. It is reasonable to state that the large deviations from the median bioimpedance were the effect of higher temperature and higher frequencies. This phenomenon requires further in depth analysis however the following is a suggestion of what might be occurring:

The cell acts as a capacitor with ICF and ECF acting as conductors separated by a dielectric, the cell membrane[7]. Ions are the charge carriers in the human body. Ions flow in and out of the cell, under the control of various mechanisms of the ion channels in the cell membrane, to maintain charge equilibrium between the intracellular and extracellular environments. At resting potential of a cell the intracellular environment is slightly negatively charged while the extracellular environment is slightly positively charged. When AC current is applied to the cell there is a disruption in the resting potential of the cell and charge will build up either inside or outside the cell depending on the needle position. At body temperature the ion channels respond more like they would in vivo and so to establish resting potential again these channels open and close resulting in a fluctuation in bioimpedance of the cell (opening of ion channels = current flow, closing of channels = current impedance). At higher frequencies like 50 and 70 kHz the cell membrane acts as a better capacitor allowing more storage of current and thus larger fluctuations of bioimpedance when the ion channels open and close. Fat tissue was most affected by this phenomenon due to its high lipid content. The lipids of the cell membrane act as the dielectric and so the more lipid content the greater the ability of the capacitor to store current increasing the magnitude of the bioimpedance fluctuation in comparison to...
other tissues like muscle and border tissue. This also explains why border tissue has higher bioimpedance than muscle and greater SD from the median bioimpedance, as border tissue has a higher lipid content than muscle but less than that of fat. In order to achieve the most stable bioimpedance measurement for a tissue, in particular fat, at \(37^\circ C\) the results from this study suggest that 30 kHz is the frequency that should be used. In summary the following observations were made:

1. To avoid large SD from the median bioimpedance of tissues, fat in particular, a frequency of 30 kHz is recommended for analysis at \(37^\circ C\).
2. Bioimpedance of tissues at \(37^\circ C\) was lower than tissue bioimpedance at 12 \(^\circ C\).
3. Variable factors, species and frequency, did not have as much an effect on tissue bioimpedance at \(37^\circ C\) compared to tissue bioimpedance at 12 \(^\circ C\).
4. The same bioimpedance pattern for all tissue types emerged: Lamb demonstrated the highest bioimpedance for each tissue type at \(37^\circ C\) while beef was next but similar to pork which demonstrated the lowest bioimpedance in each tissue category.

V. CONCLUSION

This study has demonstrated that bioimpedance measured invasively using a needle (the macro-needle) similar in design to that of the ‘smart’ needle can differentiate between tissue types. The optimum frequency range for bioimpedance differentiation was determined (10 – 100 kHz regardless of temperature) and temperature was found to be inversely proportional to bioimpedance. Bioimpedance remained constant over time for most tissues analysed with the exception of fat at \(37^\circ C\) measured at 50 and 70 kHz. For this reason analysis of tissues at \(37^\circ C\) should be performed at 30 kHz. Ultimately, in conclusion, the use of bioimpedance to create the ‘smart’ needle, i.e. a miniaturized macro-needle, is feasible.

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REFERENCES