Original Article

Tissue type determination by impedance measurement: A bipolar and monopolar comparison

ABSTRACT

Background: In certain medical applications, it is necessary to be able to determine the position of a needle inside the body, specifically with regards to identifying certain tissue types. By measuring the electrical impedance of specific tissue types, it is possible to determine the type of tissue the tip of the needle (or probe) is at.

Materials and Methods: Two methods have been investigated for electric impedance detection; bipolar and monopolar. Commercially available needle electrodes are of a monopolar type. Although many patents exist on the bipolar setups, these have not as yet been commercialized. This paper reports a comparison of monopolar and bipolar setups for tissue type determination. *In vitro* experiments were carried out on pork to compare this investigation with other investigations in this field.

Results: The results show that both monopolar and bipolar setups are capable of determining tissue type. However, the bipolar setup showed slightly better results; the difference between the different soft tissue type impedances was greater compared to the monopolar method.

Conclusion: Both monopolar and bipolar electrical impedance setups work very similarly in inhomogeneous volumes such as biological tissue. There is a clear potential for clinical applications with impedance-based needle guidance, with both the monopolar and bipolar setups. It is, however, worth noting that the bipolar setup is more versatile.

Key words: Anesthesia interventions, bipolar, impedance, monopolar, soft tissue

Introduction

In certain medical applications, it is necessary to be able to determine the position of a needle inside the body, specifically with regards to identifying certain tissue types. By measuring the electrical impedance of specific tissue types, it is possible to determine the type of tissue the tip of the needle (or probe) is in as it is pushed into the body.[1] This has the potential for clinical applications where determining the location of the needle tip is necessary, such as regional anesthesia. Currently, the needle tip location is determined through a number of methods, the most common ones are tactile sensations, i.e., the feel of the physician, X-rays or ultrasound imaging, and peripheral nerve stimulation (PNS). These methods have inherent drawbacks; published data predict that 1 in 23,500 to 50,500 spinal anesthetics and epidural procedures result in permanent harm to the patient.[2] The feel of the physician is subjective; X-ray imaging cannot visualize soft tissues; ultrasound imaging

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has the limitation of a two-dimensional (2D) display, and the equipment is also expensive (£20,000 to 70,000), PNS can be uncomfortable for the patient while providing only limited feedback regarding the proximity of the needle tip to the target nerve. The use of impedance based needle guidance has been investigated since the 1930's.[3] Numerous methods have been researched, however, in more recent years, a monopolar setup has been extensively studied at the University of Oslo.[4-7] In these recent investigations, it was suggested, but without evidence, that a monopolar setup would be superior to a bipolar setup in inhomogeneous volumes, such as human tissue.[6] The monopolar setup was found to measure the impedance of tissue within a spherical volume with radius 3–4 times that of the radius of the electrode at the needle tip.[7] Our hypothesis is that a bipolar setup would give better results as both electrodes are, in general, within the tissue being measured. The bipolar setup would also be easier to implement as an external electrode is not needed. The objectives of the investigation in this paper are thus to compare bipolar and monopolar measuring setups and determine if one setup is inferior/superior to the other. An investigation of the potential applications of the technology including discrimination of nerve tissue and cerebrospinal fluid (CSF) through experimental procedures is also carried out. The merits of both setups in tissue type discrimination are discussed.

Materials and Methods

All monopolar and bipolar measurements were taken with the same equipment. The impedance measuring device was developed in the Wolfson School of Mechanical and Manufacturing Engineering and uses a constant current source[8] to calculate the impedance of the tissue with an accuracy of 1.3%. The constant current source is calibrated to 86 kHz and 0.5 mA. The frequency chosen is appropriate as it is high enough to overcome the capacitive nature of the cell membrane, ensuring the current flows through the intracellular fluid of the desired cells and not around them via the extracellular fluid.[9] By increasing the current significantly there is a higher risk of increased effects from the polarization of the cell membrane. Furthermore at very high frequencies, polarization of the water molecules may occur.[1] The needle was mounted to a constant feed rate rig, which uses a stepper motor and a lead screw to convert the motor rotation into linear motion. The feed rate for all the experiments was set to 1 mm/s, with impedance readings taken every 0.02 s, resulting in measurements taken every 0.02 mm. Stimuplex insulated nerve block needles, 20-gauge, 30° bevel and 150 mm long were used. These needles are electrically insulated excluding the very tip which acts as an electrode. All experiments were repeated numerous times to ensure the validity of the results.

Monopolar setup

This is illustrated in Figure 1. In this setup, only one electrode is present at the needle tip. The current passes from the needle tip to the reference electrode through the volume in-between. The surface area of the reference electrode is much greater than that of the needle tip and as such the current density at the needle tip is much greater. As a result, the measured impedance reflects the impedance of a small volume around the needle tip electrode.[5]

Bipolar setup

This is illustrated in Figure 2a and b. In this setup, two electrodes are present at the needle tip. Both electrodes contribute to the measured impedance, the current passes from one electrode to the other through the small volume of tissue between them. To represent this setup, two of the Stimuplex needles mentioned previously were fastened side by side to give a representative setup of a bipolar needle (i.e., two electrodes next to each other). In clinical applications, a biaxial needle with a dielectric separating the two conductive layers could be used,[10] or a stylet type needle where the stylet acts as the second electrode and is removed once the target location is confirmed.

In vitro experiments

The pork was used because it has similar properties to that of human tissue and it has been widely used in other

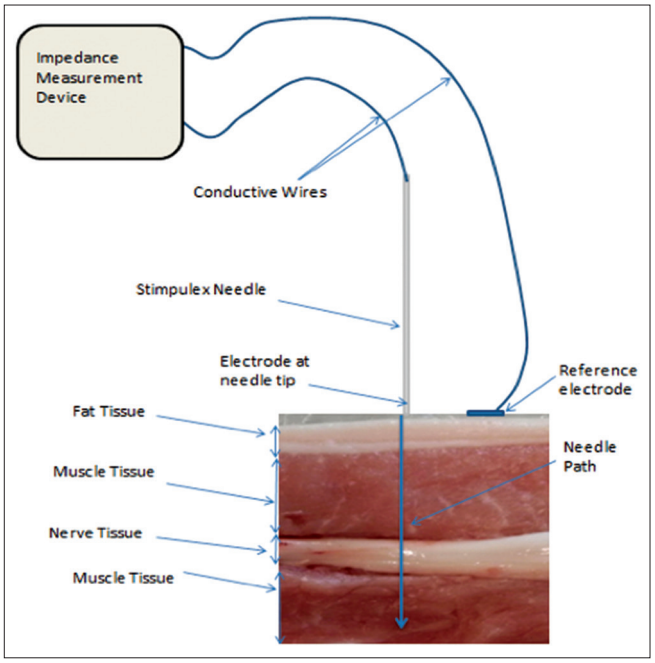

Figure 1: Monopolar electrical impedance measurement setup

investigations in this field. *In vivo* tests were unfortunately not possible in this investigation. However, research in this field confirms that *in vitro* tests reflect results seen in *in vitro* tests.[3,5] As such the *in vitro* tests on pork will allow adequate comparison between the setups under investigation.

Method validity (Test 1)

Supermarket bought bacon was used to replicate the monopolar experiments carried out at the University of Oslo.[6] Bipolar tests were also carried out on the same bacon for comparison. The needle entered the bacon through the fat and progressed to the muscle. This was repeated for both monopolar and bipolar measurements with the needle paths very close to each other to enable comparison to be made.

Nerve detection (Test 2)

This test was designed to investigate the ability of the setups to detect nerve tissue. An arrangement comprising a thick pork chop with a cavity in the muscle extruded and nerve tissue from the spinal cord of a pig inserted into this cavity was used. The needle advanced through a layer of fat tissue, followed by muscle, then into the nerve tissue and back out of the nerve tissue into a muscle once again. Similar to Test 1, the experiment was repeated with both monopolar and bipolar setups in very proximity in the pork to enable comparison.

Cerebrospinal fluid detection (Test 3)

This test was designed to investigate the detection of CSF using both monopolar and bipolar setups. An arrangement comprising of a thick pork chop partially submerged in a reservoir of CSF substitute (Prismasol® 4, Gambro, Renal replacement solution) was used. The needle advanced through fat tissue, muscle tissue and into the CSF substitute reservoir. Both monopolar and bipolar setups were tested with needle paths in very proximity in the pork sample.

Results

Figure 3 gives the results for the validity experiments. Impedance measurements at $\Delta t = 0.02$ s and a constant feed rate of 1 mm/s in bacon are shown for both monopolar and bipolar setups. The results have similar trends in bacon, with the bipolar setup giving larger amplitudes compared to the monopolar setup. The impedance of the muscle tissue in the bacon is significantly lower in both setups, with an average of 0.23 kΩ with the monopolar setup and 0.30 kΩ with the bipolar setup. The impedance measurements of the fat tissue fluctuate significantly in both setups due to the inhomogeneous makeup of the fat tissue. However, the impedance measured for fat is significantly higher, by several orders of magnitude, with a minimum impedance of approximately 2 kΩ. The change in tissue type from fat to muscle is indicated by a sudden drop in impedance followed by constant low impedance with relatively small amounts of fluctuation representing muscle tissue.

Figure 4a gives the results for the CSF substitute detection experiments using pork samples, with the needle traveling through fat, muscle and into a CSF substitute reservoir. Similar to the previous results, the fat area is indicated by large impedance amplitudes with significant fluctuations

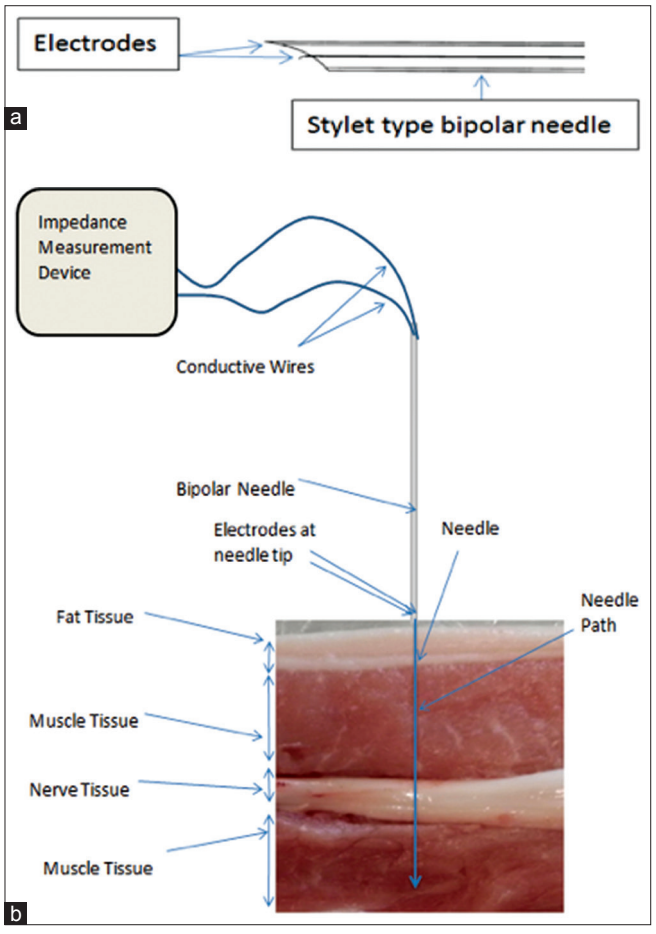

Figure 2: (a) Example of bipolar needle, (b) bipolar electrical impedance measurement setup

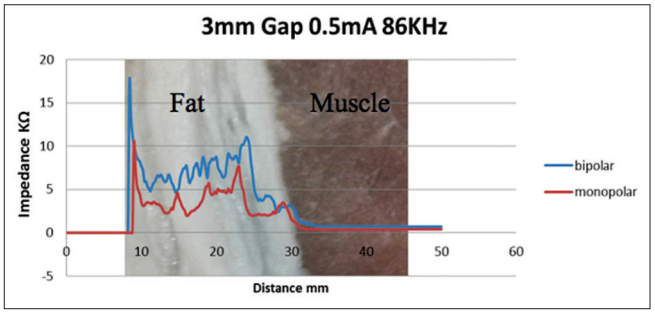

Figure 3: Method validity - impedance measurements at Δt = 0.02 s and constant feed rate of 1 mm/s in bacon

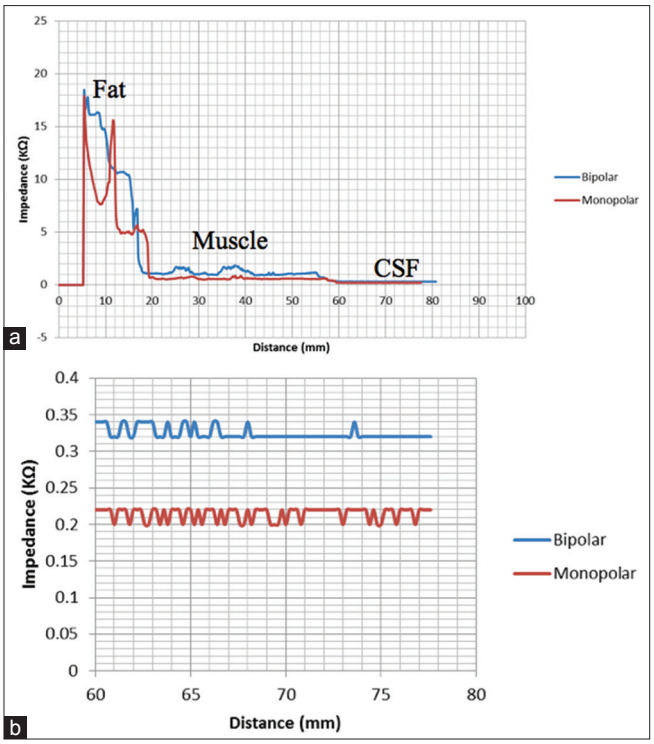

Figure 4: (a) Cerebrospinal fluid detection - impedance measurements Δt = 0.02 s and a constant feed rate of 1 mm/s in pork traveling through fat, muscle and into cerebrospinal fluid substitute reservoir, (b) cerebrospinal fluid detection – magnification of cerebrospinal fluid substitute impedance values

for both setups. The minimum impedance of pork fat tissue is approximately 5 kΩ. Furthermore, at the transition from fat tissue to muscle tissue, a sharp drop in impedance to a relatively constant low level, with small fluctuations between 1 and 2 kΩ, is seen for both setups. Another noticeable drop for both setups is seen at the transition from muscle tissue to CSF substitute. The impedance of CSF substitute is very low as shown in Figure 4b. In general, the bipolar setup gives a larger difference between measured impedances of the different tissue types.

The results of nerve detection experiments are shown in Figure 5. The impedances of fat and muscle tissues are similar to previous results. Nerve tissue is shown to have higher impedance compared to muscle and lower impedance compared to fat tissue. The nerve tissue impedance peaks to just over 4 kΩ for both setups.

Discussion

The main purpose of the method validity test (Test 1) was to confirm that the monopolar setup gives similar results to published work by others, and to also establish the difference between the bipolar and monopolar setups in the same tissue samples. The ability to compare the results undertaken in

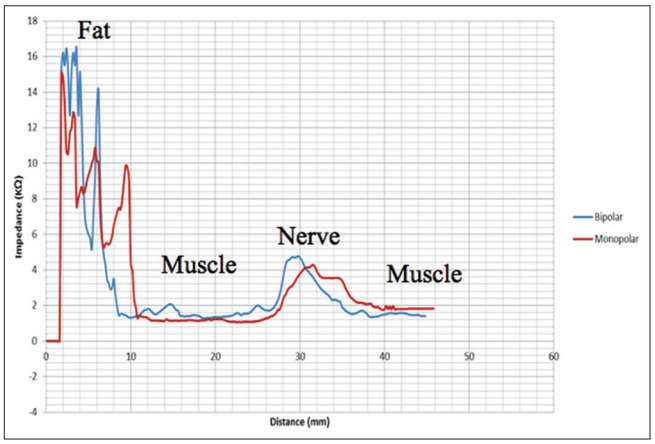

Figure 5: Nerve detection - impedance measurements Δt = 0.02 s and a constant feed rate of 1 mm/s in pork traveling through fat, muscle, nerve, and back to muscle

this study to those in other publications[5] allows confident confirmation that the adopted technique is suitable for comparison purposes. It has been shown that both the monopolar and bipolar setups give similar results in general. Bacon, which was used in other studies,[5] has a good linearity in tissue composition, creating clear fat to muscle transitions. However, it undergoes processing such as smoking which alters the impedance values and results in greater variances between different packs of bacon. Hence, the impedance values measured in Test 1 are different to those published by Kavloy[5] but the trends are the same. Thus, bacon was used only for Test 1. Pork chops, which are not processed and are the closest to human tissue for *in vitro* tests, have been used in the subsequent experiments. For the bacon experiments in Test 1, the only notable difference between the two setups is the greater difference between the measured impedances of fat and muscle tissues in the bipolar setup. This could be advantageous as a larger difference in tissue impedances reduces the uncertainty of needle location.

CSF substitute detection in Test 2, confirms the possibility of applying the impedance measurement technology to spinal anesthetic injections. The current procedure requires the physician to wait until CSF can be seen flowing back through the needle. This often takes 30 s, and can take longer in the more difficult cases, such as obese patients, dehydrated patients with dry taps, and the elderly with calcified ligaments. The results show that it is very easy to discriminate CSF substitute from muscle and fat tissue, by both the magnitude and lack of fluctuation of the measured impedance. The mean impedance of CSF is approximately 0.32 kΩ for the bipolar setup and 0.21 kΩ in the monopolar setup with a very small fluctuation 0.02 kΩ in both. The lack of fluctuation and low impedance are expected of a homogenous volume (inherent from a liquid solution) with

an abundance of ions. The results also show that the bipolar setup shows a larger difference between the measured impedances of different tissue types, especially between muscle and CSF substitute.

Results of Test 3 show promise for peripheral nerve block procedures. In these procedures, the closer the anesthetic is injected to the nerve, the better the quality of anesthesia. Damage can occur if the anesthesia is injected directly into the nerve and, as a result, a trade-off, between safety and quality of anesthesia, can occur due to the uncertainty in the resolution and the 2D nature of ultrasound technology. The results show that a relatively sharp rise in impedance can be seen when the needle tip comes into contact with nerve tissue within muscle tissue. However, it would be difficult to identify nerve tissue when it is within fat tissue because of the large impedance fluctuations of fat tissue. It is most common for the target nerve to be located in fascia, which has similar properties to muscle, in this case, the nerve could be easily identified by impedance measurements. Locations, where fat tissue neighbours nerve tissue could be identified with ultrasound technology as fat, has greater echogenicity than muscle or fascia. Where possible these areas could be avoided in favour of nerves within fascia or muscle. While both setups show clear ability to aid in this procedure, it is worth noting the sharper peak in impedance at the muscle to nerve tissue transition with the bipolar setup. This will be advantageous in identifying nerve tissue more clearly.

Though a relatively higher tissue differentiation could be deduced using the bipolar setup, from the *in vitro* experiments carried out, it is very difficult to predict which setup is the more sensitive because of tissue compliance and variability in tissue structure. The tissue volume measured is in proportion to the needle tip, which is inherently very small, and tissue compressibility makes it extremely difficult to predict the exact location of the needle tip within a volume of tissue. Such compressibility also affects the quality of contact of the electrode with the tissue. The compressible and inhomogeneous nature of tissue results in the fluctuations seen in the impedance measurements, especially in fat tissue. While, as seen with CSF substitute, when the electrodes are in a homogenous volume with a constant quality of contact, the measured impedance shows almost no fluctuations.

It should be noted that heating effects to tissue volumes are not a risk associated with this method. The frequency of the alternating voltage and the low current used in impedance measurements do not have any adverse effects.[11] The temperature of the test samples was measured during the aforementioned experiments over 5 min and no temperature rise was seen.

The bipolar setup shows a larger difference between the impedance measurements of different tissue types and sharper peaks at tissue transitions. There are also greater fluctuations in muscle tissue impedance measurements; this is indicative of a smaller sensitivity zone (volume of tissue contributing to measured impedance) associated with the bipolar setup. The smaller sensitivity zone results in a smaller volume of tissue being measured. Hence, the measured impedance would be more exposed to the inhomogeneous nature of tissue. For example, in muscle, fat pockets would form a larger portion of the measured volume. This explains the greater fluctuation seen in the muscle regions of Figures 4 and 5 with the bipolar setup.

The experiments were carried out in Mechatronics in Medicine and Research Laboratory at Loughborough University, Loughborough, Leicestershire, UK. Although this is not representative of *in vivo* conditions, i.e., in patients, the effect of temperature on impedance measurement has been widely confirmed. Temperature and impedance of biological tissue are inversely proportional; as temperature increases the resistance of the tissue decreases.[3]

The impedance values of pork fat, muscle, and nerve tissues in Laboratory will be different from those of a healthy human. Human testing was not an option in this investigation. However, other research has confirmed that the monopolar setup can discriminate between tissue types in a healthy human.[5] In this investigation, the bipolar setup has produced results very similarly to the monopolar setup in all experiments. It can, therefore, be assumed that it would produce similar results to the monopolar setup in a healthy human.

Conclusion

In all the experiments, both the monopolar and bipolar setups showed the ability to discriminate between muscle, fat, nerve and CSF substitute. Results from this investigation align very well with other research in the field. The exception to this is the hypothesis by Stubhaug *et al*.[6] that a bipolar setup would not work well in inhomogeneous volumes. In fact, our results show that both setups work very similarly in inhomogeneous volumes such as biological tissue. There is a clear potential for clinical applications with impedance based needle guidance, with both the monopolar and bipolar setups. The portability and low-cost nature of impedance measurement systems would be attractive commercially, while reducing the risk of complications during anesthetic procedures. It is, however, worth noting that the bipolar setup is more versatile. The current path in

the bipolar setup is localized to the small volume of tissue between the two electrodes, whereas with the monopolar setup the current passes through the body via any route to the surface electrode. In cases where the patient has metal implants such as hip replacements or internal electronic devices such as pacemakers or internal cardiac defibrillators the monopolar setup will be unsuitable as the current could interfere with internal electronic implants depending on the current paths and the sensitivity of the device; the impedance measurements will also be affected by the metal implants. The major advantage of the bipolar setup is that it is not affected by such cases. Further investigations on live animals and eventually humans are needed; however, the results from this investigation are very promising for impedance based needle guidance, for both monopolar and bipolar setups.

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Conflicts of interest

There are no conflicts of interest.

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