A New Bioimpedance Research Device (BIRD) for Measuring the Electrical Impedance of Acupuncture Meridians


Abstract

Objectives: The aim of this article is to introduce an electrical bioimpedance device that uses an old and little-known impedance measuring technique to study the impedance of the meridian and nonmeridian tissue segments.

Design: Three (3) pilot experimental studies involving both a tissue phantom (a cucumber) and 3 human subjects were performed using this BIRD-I (Bioimpedance Research Device) device. This device consists of a Fluke RCL meter, a multiplexer box, a laptop computer, and a medical-grade isolation transformer. Segment and surface sheath (or local) impedances were estimated using formulae first published in the 1930s, in an approach that differs from that of the standard four-electrode technique used in most meridian studies to date.

Results: Our study found that, when using a quasilinear four-electrode arrangement, the reference electrodes should be positioned at least 10 cm from the test electrodes to ensure that the segment (or core) impedance estimation is not affected by the proximity of the reference electrodes. A tissue phantom was used to determine the repeatability of segment (core) impedance measurement by the device. An applied frequency of 100 kHz was found to produce the best repeatability among the various frequencies tested. In another preliminary study, with a segment of the triple energizer meridian on the lower arm selected as reference segment, core resistance-based profiles around the lower arm showed three of the other five meridians to exist as local resistance minima relative to neighboring nonmeridian segments. The profiles of the 2 subjects tested were very similar, suggesting that the results are unlikely to be spurious.

Conclusions: In electrical bioimpedance studies, it is recommended that the measuring technique and device be clearly defined and standardized to provide optimal working conditions. In our study using the BIRD I device, we defined our standard experimental conditions as a test frequency of 100 kHz and the position of the reference electrodes of at least 10 cm from the test electrodes. Our device has demonstrated potential for use in quantifying the degree of electrical interconnection between any two surface-defined test meridian or nonmeridian segments. Issues arising from use of this device and the measurement Horton and van Ravenswaay technique were also presented.

Introduction

Electrical bioimpedance is a widely used technique that has been used to investigate the existence of acupuncture points and meridians. For more than half a century, acupuncture meridians, which are considered by many in the acupuncture community to be special conduits for electromagnetic energy, have been reported as having lower bio-electrical impedance compared to adjacent controls. However, the interpretation of the evidence to support the existence of meridians as electrical pathways remains controversial, possibly due to various confounding factors such as the use of nonstandardized techniques and measuring devices, variations in measuring conditions, and the physical characteristics of the test populations (body build, ethnicity, age, etc.) in these studies.
In acupuncture meridian studies, the body’s connective tissue network is attracting ever-increasing theoretical and research attention.\textsuperscript{3,7–11} Not surprisingly, therefore, bioimpedance investigations of the skin and subdermal connective tissues have constituted a major line of research related to this theme.

A key question that arises in relation to such studies is: Do the acupuncture meridians represent preferential electrical pathways throughout the connective tissues? Interestingly, investigation of the body’s current pathways has also been identified in a National Institute of Health assessment conference statement as important for better understanding of the scientific underpinnings of bioimpedance analysis, technology commonly used for body composition determination.\textsuperscript{12} Even the current pathways from internal organ to skin surface associated with such commonly used clinical devices such as electrocardiographs and defibrillators are presently poorly understood.\textsuperscript{13} Therefore, investigations directed toward mapping out the body’s electrical pathways constitute a worthwhile basic area of research. The aim of this article is to introduce a new device that uses an old but flexible impedance measuring technique and to present some of our preliminary findings. It is expected that the methodology developed in this study will serve as a basis for new approaches toward investigation of the electrical properties of the acupuncture meridians.

Materials and Methods

Subjects

The subjects in this study were 3 healthy researchers, 2 female Asian medical students (M.F. and V.W.) and the other a white male scientist (W.S.). The second experiment included in this article was performed on a tissue phantom—a fresh large cucumber bought from a supermarket. The experiments were performed in the Chinese Medicine Clinical Research Centre in Liverpool Hospital. This study was approved by the Human Research Ethics Committee of the University of New South Wales.

Instrumentation

The bioimpedance device (BIRD I–Bioimpedance Research Device I) used in this study was assembled as a prototype by Eureka Medical Impedance Technology Pty Ltd. (EMIT). Two-electrode impedance data were acquired by using a Fluke RCL meter, Model PM6306 (Everett, WA), which supplied a constant voltage of 1.00 V at any combination of five available test frequencies: 5, 10, 20, 100, and 200 kHz.

A laptop computer was used to initiate the measurements via serial communication to the Fluke meter. Using a scheduler (text) file, measurement tasks were set up and run without the need for user intervention. Output data were automatically saved in an easy-to-read CSV (Comma Separated Values) format. These CSV files could then be imported into a wide range of analysis and reporting tools including Excel. There was a User Interface that provided a visual display of the scheduled tests being run. The automation of this entire system was programmed using 4Control supplied by Ti2 Pty Ltd. (Sydney, Australia). 4Control is an industrial automation package that is specifically designed to control, communicate, and collect data, using industrial standards such as IEC61131 programming and OPC connectivity. All the components of the BIRD-I device are shown in Figure 1.

Impedance measurements by the Fluke meter were pre-selected to be output as a series combination of resistance and capacitance. The BIRD I device can accommodate up to 26 input channels. Predefined electrode combinations were sequenced using the PC Scheduler and routed from the multiplexer unit to the Fluke RCL meter. Measurements of electrode combinations were typically carried out in cyclic order whereby the initial measurement sequence was repeated in reverse order back to the first electrode combination tested. To ensure subject safety, the Fluke RCL meter was connected to the main supply through a medical isolation transformer. The device was calibrated using precision resistors.

All acupuncture points and meridians selections were performed by an accredited acupuncturist. Single-use disposable adhesive gel electrodes (Ambu Blue Sensor BRS-50-J [Denmark], 19 mm x 16 mm) were used in conjunction with an adhesive ring with an internal diameter of 7.5 mm (Grass Product Group) to accurately control the skin contact area. These commercially available electrocardiogram/ electromyogram electrodes, which are commonly used in pediatrics for long-term monitoring, were positioned on pre-selected test sites and connected by wire lead to the multiplexer unit of the BIRD I system.

Technique

The fundamental but little known combinational two-electrode technique first documented by Horton and van Ravenswaay in 1935—and which we shall refer to as the HvR technique—was adopted for our BIRD I-based meridian bioimpedance measurements\textsuperscript{13} (Fig. 2). In essence, the technique is based on the model that total impedance between any two surface electrodes can in general be decoupled into two types of components: surface sheath (or local) impedances associated with each electrode and a core (or nonlocal) impedance between the two electrodes. The former is con-
sidered to include contributions from the electrode, from the electrode-to-skin contact impedance and from upper layers of the skin, while the latter is considered to relate to vaguely defined subdermal tissue. As far as we are aware, the HvR technique itself was essentially abandoned back in the 1930s and largely superseded by the now well-known standard four-electrode technique. While Horton and van Ravenswaay\textsuperscript{13} did suggest that their technique had considerable flexibility, the two major objections given by the authors were the following:

1. The technique was considered cumbersome and tedious because of the large number of readings required and the need for computation.
2. The technique was inaccurate since small differences in impedance had to be detected against relatively large background total impedances.

With the ready availability of computerized, high-accuracy impedance equipment, these two objections can now largely be overcome or minimized. We therefore decided to reexplore the use of the HvR technique, taking advantage of its very flexibility in attempts to gain new insights into the electrical properties of the acupuncture meridians.

Referring to Figure 2, the following key equations, derived using simple algebra, allow the respective HvR parameters to be determined simply from combinations of two electrode impedance measurements on the skin surface:

**Surface Sheath Impedances at B and C (Z\textsubscript{SB} and Z\textsubscript{SC}):

\[
Z\textsubscript{SB} = \frac{Z\textsubscript{T}(AB) + Z\textsubscript{T}(BC) - Z\textsubscript{T}(AC)}{2}
\]

where \(Z\textsubscript{T}(AB)\), \(Z\textsubscript{T}(BC)\), and \(Z\textsubscript{T}(AC)\) represent total impedance between electrodes A and B, B and C, and A and C, respectively.

\[
Z\textsubscript{SC} = \frac{Z\textsubscript{T}(BC) + Z\textsubscript{T}(CD) - Z\textsubscript{T}(BD)}{2}
\]

where \(Z\textsubscript{T}(BC)\), \(Z\textsubscript{T}(CD)\), and \(Z\textsubscript{T}(BD)\) represent total impedance between electrodes B and C, C and D, and B and D, respectively.

**Core Impedance in the segment BC (Z\textsubscript{C(BC)}):

\[
Z\textsubscript{C(BC)} = \frac{Z\textsubscript{T}(AC) + Z\textsubscript{T}(BD) - Z\textsubscript{T}(AB) - Z\textsubscript{T}(CD)}{2}
\]

**Core Impedance Crossover Difference between BC and AD (DZ\textsubscript{C(BC \leftrightarrow AD)}):

\[
DZ\textsubscript{C(BC \leftrightarrow AD)} = Z\textsubscript{T}(AC) + Z\textsubscript{T}(BD) - Z\textsubscript{T}(AD) - Z\textsubscript{T}(BC)
\]

This DZ\textsubscript{C} parameter can be considered a measure (in impedance terms) of the extent to which the actual situation deviates from the ideal arrangement shown in Figure 2. Figure 2 assumes that the core pathway from B to C is in common with that from A to D. This, however, will not typically be the case for any general arrangement of four electrodes. Interestingly, Horton and van Ravenswaay\textsuperscript{13} were also aware of this implicit assumption but judged it to be unimportant for the purposes of their study. We anticipate, however, that this deviation of actual from ideal, as reflected in the DZ\textsubscript{C} value, may offer a means of quantifying the degree of electrical interconnection between any two surface-defined pathways BC and AD.

In this preliminary research study using the HvR technique, emphasis is directed toward the investigation of the performances of the BIRD I bioimpedance system under the following three experimental arrangements.
Experiment no. 1. Two (2) test participants were each in turn asked to sit in a chair with the right arm resting on a cushion with the palm facing upwards. Electrodes were placed on the subject’s right forearm and foot, as shown in Figure 3. The selected test tissue segment (FG) was 86 mm in length, 70 mm distal to the elbow crease and along the line of the pericardium (PC) meridian. Pairs of “reference electrodes” were positioned symmetrically with respect to segment FG along the PC meridian (E and H, D and I, B and K, C and J) and also in one case asymmetrically in a PC/spleen meridian combination (A and M). This electrode arrangement was intended to establish the relation between reference-to-test electrode distance and core impedance with a view to defining an optimum distance for later experiments. This experiment was carried out at an applied frequency of 20 kHz.

Experiment no. 2. Four Ambu electrodes (A, B, C, and D), each with adhesive washers, were placed in a line on the surface of the tissue phantom, a fresh cucumber, as shown in Figure 4. Sets of six two-electrode impedance measurements (AB, AC, AD, BC, BD, and CD) were then carried out at each of the applied frequencies 10, 20, 50, 100, and 200 kHz, in that order, for a total of 15 repetitions and then in the reverse frequency order of 200, 100, 50, 20, and 10 kHz also for 15 repetitions. The average core resistance (Rc (BC)) at each frequency for each set of 15 repetitions was calculated and used to determine the frequency that provides optimum repeatability of core impedance (resistance). It is intended that use of such a biological test phantom will allow instrumental noise associated with the BIRD I test system to be decoupled from “noise” associated with processes in the living body (blood flow, subtle body movements, etc.).

Experiment no. 3. Each of the 2 test participants sat in a chair with feet resting on the ground and right arm resting on a cushion with the palm facing upwards. Points on meridians and nonmeridians (Fig. 5) were selected for investigating the existence of preferential conducting pathways and electrical interaction between tissue segments. Due to the large size of our electrodes, the electrodes encircling the transverse wrist crease could not be arranged in a single line, hence the alternating arrangement in two lines near the wrist crease. From the result in Experiment No. 2, a test frequency of 100 kHz was used in this experiment. The TE and HT segments, which were selected at random as reference segments from among the six-arm meridian segments, are identified as segments QR and AB, respectively, in Figure 5. The aim of this exploratory experiment was to determine whether the BIRD I device could detect any pattern in electrical properties of tissue segments around the forearm that might be suggestive of differences in core impedances of meridian and neighboring nonmeridian tissue segments.

Results

Experiment no. 1

Referring to Figure 6, the variation of core resistance (Rc(FG)) and core reactance (Xc(FG)) relating to the test-to-reference electrode distance showed several key trends. First, the forms of the curves were quite similar for the 2 participants. Second, the measured values from the initial (first) and repeat (second) sets of combinations were relatively consistent. Third, considering Figure 6 (left), with reference electrodes positioned within about 3.4 cm of the test electrodes, the measured core resistance of test segment FG is in...
Acupuncture meridians are traditionally believed to constitute channels for *qi* flow connecting the surface of the body.
to internal organs. Studies that have attempted to define the effect of acupuncture based on anatomy and physiology have described only subtle differences in the interstitial connective tissue architecture around acupuncture points compared to nearby nonacupuncture areas. These studies have also observed greater abundances of local neural and vascular connections. Some texts have also suggested that the effects of acupuncture needling may be mediated by neuropeptide modulation of neural networks localized connective tissue responses. de Vernejoul and Darras (1992) infused radioactive tracer into acupoints and demonstrated that it migrated along a meridian channel, while Zhang et al. (2008) also found a lower hydraulic resistance channel along meridians. However, these interesting experiments did not demonstrate definitely the anatomical positions of these channels or structures. Alternatively, theories regarding acupuncture meridians as "transmission lines" suggest that meridians may represent networks of preferential electrical current flow. These lines may also represent how the local sensations of acupuncture needling may be propagated. Table 2 lists a number of studies that have suggested that there might be lines or zones of differential impedance in the body that may correspond to the meridians (channels) of Chinese acupuncture.

Our study has revealed three main findings that have implications for optimizing impedance measurement repeatability in our study and possibly also for other groups using different impedance measuring devices.

![Table 2. Summary of Key Electrical Bioimpedance Studies in Acupuncture](image)

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**Table 2. Summary of Key Electrical Bioimpedance Studies in Acupuncture**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Design</th>
<th>Sample size</th>
<th>Site of testing corresponding to acupuncture points/meridians</th>
<th>Electrical current</th>
<th>Evidence (+ = positive evidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reichmanis et al.</td>
<td>Calculated resistance, capacitance</td>
<td>10</td>
<td>LI 4–LI 12</td>
<td>DC, 1 V</td>
<td>+</td>
</tr>
<tr>
<td>(1975)</td>
<td>between two acupoints on same</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhang et al. (2004)</td>
<td>Measured impedance using four-electrode method</td>
<td>12</td>
<td>Pericardium meridian around PC3</td>
<td>AC, 5 kHz</td>
<td>+</td>
</tr>
<tr>
<td>Martinsen et al.</td>
<td>Surveyed skin with a linear array of electrodes to find low-resistance pathways</td>
<td>20</td>
<td>Volar aspect of arm</td>
<td>AC, 418 Hz</td>
<td>-, no significant association</td>
</tr>
<tr>
<td>Johng et al. (2002)</td>
<td>Measured impedance across multiple frequencies using four-electrode method</td>
<td>30</td>
<td>Pericardium meridian around PC3</td>
<td>AC, 0.1–14 kHz</td>
<td>+</td>
</tr>
<tr>
<td>Ahn et al. (2005)</td>
<td>Measured impedance of meridian-associated connective tissue: four-electrode method</td>
<td>23</td>
<td>Pericardium and spleen meridian</td>
<td>AC, 3.3 kHz</td>
<td>±, mixed result</td>
</tr>
<tr>
<td>Lee et al. (2005)</td>
<td>Measured bidirectional resistance between two acupoints and between acupoint and nonacupoint</td>
<td>20</td>
<td>LI 4–LI 11</td>
<td>DC, 1.28 V</td>
<td>+</td>
</tr>
</tbody>
</table>
First, for reliable body core measurement on the upper limbs using the HvR four-electrode method, reference electrodes should ideally be 10 cm or more from the test electrodes. This will reduce errors associated with electrode positioning. This finding has parallels with that of Rutkove et al. in 2005, who used the standard four-electrode method and reported that beyond a distance of 10–15 cm between current and voltage electrodes, the “spatially averaged phase” on the forearm flexor surface also reached a plateau. With the electrodes spaced far apart, it is commonly accepted that the predominant current pathways are located in vaguely defined “deeper layers” that are considerably less resistive than the high-impedance epidermal layers of the skin surface. Second, a test frequency of 100 kHz has been found to give good repeatability in core resistance determinations on a biological (cucumber) tissue phantom and appears suitable for ongoing testing involving human subjects. With increasing frequency, it has been shown that the relative contributions from the epidermal layers to the total impedance decrease. Therefore, it is expected that estimations of underlying core resistances would be improved in terms of accuracy and repeatability by using a higher frequency.

Third, from a more general viewpoint, a key outcome of our research is the confirmation of the usefulness of a little-known four-electrode technique that differs from the standard four-electrode method long considered the “gold standard” in biophysical sciences for measuring bioimpedance. The usual reasons given for using the standard four-electrode over two- or three-electrode methods are because of its better repeatability and its ability to exclude skin impedance. However, the standard four-electrode method has its own limitations as pointed out in the work of Grimes and Martinsen and Aaron et al. These include the need to assume that the equipotential surfaces due to the applied current lie perpendicular to the skin surface and that body core impedance determinations are independent of the thickness of the skin subcutaneous layer. In comparison, the HvR four-electrode technique offers advantages of increased freedom in terms of electrode placement options as well as generating more complete information pertaining to the biological system under study. Besides measuring core resistance and reactance, this technique can also be used to determine surface sheath (or local) resistance and reactance beneath the electrode. In addition, as demonstrated in experiment no. 3 in this article, the technique can also be adapted to quantify the degree of electrical interconnection between any two test segments. As a result, a number of new research directions can be readily be explored using this method.

Nevertheless, a possible limitation identified in this study relates to the size of the electrodes. The use of relatively large-sized electrodes (19 mm × 16 mm) in conjunction with adhesive rings in this study has prevented use of more ideal electrode arrangements. This may also have lead to inappropriate point localizations, particularly since the diameter of a typical acupuncture point and width of a meridian is unknown. If the acupoints were 1.5 mm in diameter as suggested by Hyvarinen and Karlsson, the skin contact area used in this study (diameter 7.5 mm) could, for example, be considered too large. Future research using electrodes of smaller diameter appears warranted based on these present findings. In addition, studies aimed at comparison of the HvR and standard four-electrode methods will allow data from the former method to be directly compared with the large existing body of bioimpedance knowledge in both acupuncture and nonacupuncture fields.

In conclusion, this report introduces application of a little-utilized impedance technique, the HvR method, to basic electrical investigation of the acupuncture meridians and presents some preliminary examples to demonstrate its potential. With a view to eventually establishing a set of standardized experimental conditions for electrical studies of the meridians, 1.0VAC at 100 kHz has been found to be suitable in terms of data repeatability. In terms of reference electrode positioning, it is recommended that reference electrodes ideally be positioned at least 10 cm from the test electrodes. Finally, further investigations into the specifics of the interconnections between meridians using this HvR technique will be of interest, possibly with the assistance of mathematical modeling, and are expected to provide insights into the architecture of the current pathways in the arm section of the body.

Acknowledgments

The authors would like to acknowledge the support of Polartecnics Ltd. for the loan of the Fluke RCL meter used in the BIRD I device. In addition, we would also like to thank Ms. Veronica Wong and Ms. Ming Fong Yee, two wonderful medical students, for their assistance in this project. Last but not least, we also would like to acknowledge the technical advice and support of staff from Eureka Medical Impedance Technologies (EMIT) for their continual improvements to the BIRD I device used in this study.

Disclosure Statement

No competing financial interests exist.

References


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