Measuring the ELF response of an acupuncture meridian compared to a control channel

Keith Spaulding

University of New Hampshire, Durham

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MEASURING THE ELF RESPONSE OF AN ACUPUNCTURE MERIDIAN
COMPARED TO A CONTROL CHANNEL

BY

KEITH SPAULDING
BSc, Tulane University, 1988

THESIS

Submitted to the University of New Hampshire
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Master of Science
In
Electrical Engineering

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This thesis has been examined and approved.

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Date
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ABSTRACT

MEASURING THE ELF RESPONSE OF AN ACUPUNCTURE MERIDIAN
COMPARSED TO A CONTROL CHANNEL

by

Keith Spaulding

University of New Hampshire, May 2008

Acupuncture meridians are said to possess unique electrical characteristics; a characteristic of interest when analyzing systems is frequency response. The Extremely Low Frequency (ELF) response of the Large Intestine (LI) meridian was found by applying a Gaussian pulse signal to LI4 and detecting the signal at LI11; a Fast Fourier Transform (FFT) analysis is performed on this signal with a Power Spectral Density (PSD) measuring total power in the 2 – 100 Hz region. This total power is compared to the total power measurement at a control point by applying the same Gaussian pulse on a control channel; this protocol was tested on 20 participants. There was a greater power measured on the acupuncture channel compared to the control (p = 0.035 using a paired, two sided rank test) but the trend of greater signal propagation on the acupuncture channel was not as substantial as expected with six people giving the opposite result of greater power on the control channel; hence the expected result of greater power along the acupuncture channel is inconclusive.
SUMMARY AND BACKGROUND

When considering the theory of acupuncture, the acupuncture meridians play a crucial part; hence when attempting to do research on acupuncture, acupuncture meridians are a logical area of investigation. The meridians' ability to propagate a pulse compared to a control channel is studied in this thesis. Since EEGs, EKGs, and EMGs detect bioelectric signals in the ELF (Extremely Low Frequency) range, this was chosen as the range of interest. On twenty people, a Gaussian pulse, with a frequency response that is relatively constant in the frequency in the range of interest, is applied to a distal point on a meridian; the total power in the 2 – 100 Hz is calculated from the signal detected on the proximal point on the meridian. This is compared to a pulse applied to a distal point on a control channel with the total power in 2 – 100 Hz measured on the proximal point on the control channel. The difference between on channel and off channel is the parameter of interest. All electrodes, both source and detection, use acupuncture needles inserted 1 cm deep in the Chinese acupuncture style.

There have been dramatic results in earlier acupuncture research: Langevin [1] found the biomechanical response at major acupuncture points to differ from controls with a large statistical significance; also Ahn [2] found the impedance on a short part of the Pericardium meridian to be smaller than a control, again with a large statistical significance. With knowledge of these results, a much greater power was expected at the acupuncture point compared to the control point. For twenty people, using a paired, two-
sided rank test, a p = 0.035 was found showing a greater power was transferred along acupuncture meridians when compared to non-meridians of the same length. But out of the twenty people, five people gave a greater power on the control point hence the data showed only a trend rather than an unequivocal result.

**Background**

As acupuncture gains momentum as a healing modality, there is more impetus to learn the physiology of acupuncture. There has been significant precedent in studying the tissue manifestation of acupuncture, theorizing and experimenting how it materializes in the physical tissue. One area of research proposes a neurophysiologic description using dermatome patterns as a means for the needle stimulation to affect the Central Nervous System, but this does not explain the channel theory of acupuncture, an integral part of the theory. Neurohormonal theories propose that the micro damage from needle stimulation causes a release of neurohormones [3]; this explanation is particularly effective for describing acupuncture's pain relieving abilities and for the effect acupuncture has on organ related problems like gastro-intestinal disorders, but again the explanation does not follow the flavor of Chinese acupuncture theory.

A theory that better fits acupuncture theory is the connective tissue model research taking place at UVM with Dr. Helene Langevin. Needle stimulation winds connective tissue around the needle, amplifying the coupling between the needle and the local connective tissue [4]; this locally generated activity in the connective tissue now has a means to affect all parts of the body because of connective tissue ubiquity. Connective tissue planes, for example traveling proximally along two muscles, follow along the
meridians of Chinese acupuncture; also acupuncture points are shown to be convergences of these connective tissue planes [4].

If these connective tissue planes are acupuncture meridians, it would be reasonable to assume that they should have the unique electrical properties assigned to acupuncture meridians – lower resistance, better propagation, and a unique ELF response [5-9,12]; these electrical properties of acupuncture are another significant area of study in acupuncture research and the area of investigation of this research. The most common work tests the impedance of points and channels on the skin [5-9]. Yet acupuncture meridians, from acupuncture theory perspective, travel in the tissue, that are “within the lining” [10]. Consequently, the research presented in this thesis uses inserted acupuncture needles, rather than skin-attached electrodes in order to be more consistent with acupuncture theory.

Electrical Impedance is a commonly used method for studying acupuncture meridians, the measurements are generally straightforward, and the effects can be modeled using simple resistors and capacitors [11]. Yet biological tissue is active, and does not respond in the same manner as simple lumped devices [12]. Further, the often-used four electrode method may not be as accurate as originally believed [13]. The method used in this research uses a signal model where a signal is launched in the tissue and received at a point proximally where measurements are made. This approach is employed in numerous studies in acupuncture research [6-8, 14-16], yet these studies do not include control channels or control points or any statistical analysis.
When considering acupuncture point selection, with the Langevin study [1], numerous major acupuncture points throughout the body were chosen with the control adjacent to the point, and of these, Large Intestine (LI) 4 was chosen. The biomechanical response was determined at those points as well as in other tissues. Another study used inserted needles and the four electrode method; Ahn [2] measured the impedance of a short distance of the Pericardium meridian showing statistical significance of lowered impedance, but not significance in a small part of the Spleen meridian. In the research reported here, the LI meridian is the main meridian of interest not only because of ease of access, but also because it has been widely studied in earlier research. In Cohen [6] the impedance of the LI meridian is measured on the skin with results showing great variation; in Cohen [14], a biphasic pulse is used to stimulate an inserted needle on LI4 on 10 subjects, with a frequency response at LI11 showing some resonances at frequencies under 50 Hz; Lazoura [8] applied pulses to LI4 on 10 subjects, again detecting at LI11, using inserted needles, but this time the frequency response showed the least attenuation at frequencies under 20 Hz. Apart from Langevin and Ahn, statistical methods were not used in any of these studies.

Other important works in the electrical analysis of acupuncture include:

- Producing a method to measure the skin impedance for prolonged periods of time [17];
- Using the four electrode method, measuring the change of impedance on the skin before and after needle stimulation [9];
• After applying dc voltage to the skin, the dc current along the Large Intestine meridian from distal to proximal was seen to be greater than from on the channel to a point off the channel [18];

• Measuring dc current at an acupuncture point, it was seen that the current was higher when the needle was inserted with a bare hand rather than a gloved hand [18].

Electrical Current through tissue propagates as ionic current. For low frequencies, as investigated in this research, the ionic current moves mostly through extra-cellular space because of the capacitive effect of cell membranes [19]. In the signal model used in this research a Gaussian pulse as voltage source is applied to the acupuncture needle, which is the electrode, and an ionic current is induced in the tissue in all directions, not just to the input of the “receiving” electrode proximal to the source. This electrode is attached to a high impedance input of a DAQ and little current follows this path; most of the current traverses up the arm, through the body, and back to the 0 V point on the lower leg.

**Hypothesis and method summary**

By using a Gaussian pulse having a spectral content concentrated in the ELF range as the signal source, the hypothesis under consideration here states that there is a difference on the signal propagated on the LI meridian compared to a control (Ctr) channel that is not aligned with any commonly-accepted acupuncture channel. This signal is launched through a needle at a distal point on a meridian (or a control channel) and that signal is received by a needle inserted needle at a proximal point on the same meridian (or control
channel). This thesis is the result of research on volunteers of a small study to implement the method. The test configuration lies at the heart of the experiments and the data collected during the experiments were facilitated by the use of a Matlab-controlled test platform.

Two main methods of analysis are used: a graphical means of analysis produces a spectral response to better understand propagation, and power spectral density calculations with a final product of total power to create data to find a statistical difference between the signal propagation on the channel compared to the signal propagation off the channel.

For the study, a Gaussian pulse was applied to the meridian or control and measurements were made proximally both on the channel and off the channel; this test produced the ELF spectral response data as well as the power spectral density measurements used in analysis. A more detailed description of the method of the study is given in the following chapter.

As stated above, the objective of this thesis is to determine whether there is a difference between acupuncture meridians and other tissues in the way they transport low-frequency electrical signals. That determination is made empirically, and hence the methods for collecting and analyzing measured data are critical to the conclusions obtained. Accordingly, the data collection hardware and method for data analysis are described in Chapter I.
CHAPTER I

THE TEST CONFIGURATION AND METHOD OF THE RESEARCH

The method used for this research is based on a signal propagation method; the justification for this choice is described in the *Idiosyncrasies of Performing Electrical Tests on Biological Tissue* chapter. Below is a description of the test configuration, mostly the hardware and software, of the stimulus pulse, ways to test the configuration in vitro and in vivo, and a description of the analysis methods used in the results section.
Fig. 1: Test Configuration
Fig. 2: Biological current flow for this setup

Matlab and the Data Acquisition Toolbox

The test configuration hardware setup can be seen in fig. 1; its advantage is its flexibility. Over the course of the research, numerous methods were used to study and analyze the acupuncture meridians in the tissue: swept sinusoids and Gaussian pulses were used as sources, FFT and time-domain investigation were used in analysis and plotting the data, and matrix manipulation and statistical analysis were used as mathematical tools. If using separate tools this would require signal generators, data acquisition software, and another mathematical software package. All was accomplished with Matlab and a DAQ (data acquisition unit. Matlab is a powerful tool used by engineers and scientists. In one study [16] Matlab was used as a data acquisition tool, data analysis and plotting, and statistical analysis tool; in other studies [11, 17] Labview is used as a data acquisition tool. The uniqueness in this research is to utilize Matlab’s signal generating flexibility with its back end capabilities; hence it is necessary to learn only one software package to accomplish all the goals of the research.
The biological current flow is shown in fig. 2: the current is applied at LI4 (or CtrS) and flows to the point of lowest potential, Leg Ref on the lower leg which is set to equipment ground. Current is applied to LI4S and finds the path of least resistance up the arm; our assumption is that the path is the acupuncture meridian. This means that the current flows up the arm, through the thorax, down the leg and back to the equipment at Leg Ref. Because of the large impedance of the op amps in the DAQ, there is little current flowing from LI11 (or CtrB) to the DAQ.

Data Acquisition Hardware

The NI USB6211 DAQ was chosen because it has input and output capabilities; also it is powered – and with data communications – using USB. This is a benefit because the researcher performed the study on volunteers at their place of home and work with a laptop; having the DAQ thru the USB was another layer of protection from electrical transients. Below are some of the relevant specifications of the USB6211:

- 16 analog inputs multiplexed to one 250 kSamples/sec 16 bit D/A (For the study the using two input op amps, each output effectively sampled at 125 kSamples/sec)

- Input accuracy setting - 2.69 mV, sensitivity 91.6μV

- Input CMRR = 100dB, bias current = +/- 100pA

- Input impedance - > 10 GΩ in parallel with 100pF

- Output accuracy - 3.512mV

- Output impedance - 0.2 Ω
Point Selection and Reference Point

The Large Intestine meridian – located on the lateral aspect of the forearm (fig. 3) – was chosen as the meridian to be tested. It is a common meridian in acupuncture research [5, 18, 22, 23], perhaps because of its ease of access (volunteers needed only to roll up their sleeves to participate in the study). The acupuncture points along the meridian selected to study were LI4, LI8, and LI11; LI4 and LI11 are common points used in acupuncture, said to be large points in Chinese Medicine theory, and are easy to locate (see fig. 1 for the following discussion on the points). It is common in the research to pick a point that is a certain distance away, for example 2 cm; although this is measurable and repeatable, it is not always practical because of the variations from person to person (2 cm could be in muscle in one person and in bone in another person). It was considered
important to choose a control channel that a signal would propagate mostly in similar tissue (muscle and connective tissue) rather than risking propagating over bone, which would represent a significant difference in tissue type. Hence the control channel was chosen for its anatomic properties, in addition to the fact that it represented a similar distance: the CtrS was chosen on the dorsal side of the forearm, medial to the LI meridian, in the dorsal interosseous muscle, between the 2nd and 3rd metacarpal bones. CtrB was chosen the same distance away from LI11 as the distance from LI4 to CtrS. If that distance landed in the epicondyle of the humerus, then the point was chosen as close as possible to the bone but still in the soft tissue. The middle point (LI8 and CtrA) was selected to perform signal propagation tests. It was considered important to keep the length of the tested channel equidistant so there would not be any significant difference in attenuation (as it turned out, there was very little attenuation to the signal in the tissue for these distances in the <20Hz range). CtrS to CtrB was chosen to have a similar distance as LI4 to LI11.

Acupuncture points were found using standard anatomical charts [24] and from the researcher's acupuncture experience. As is typical in Chinese acupuncture theory for these points, the needle was inserted 10mm; the length was not measured. 32 AWG acupuncture needles were inserted to common insertion length from the experience of the researcher. The needles at the distal points (LI4 and CtrS) were stimulated in the Chinese acupuncture method of twirling clockwise and counterclockwise, before the pulse was applied.

Acupuncture theory was kept in mind when making decisions about point selection; and this pertained to reference selection. If the four electrode method is chosen [2, 9],
there is no need for a reference (the four electrode method is described more in *The Idiosyncrasies of Performing Electrical Tests on Biological Tissue*). With the signal propagation method, a reference is needed. The selection of the electrical reference point (i.e., electrical ground) can have a significant impact on biological measurements [12]. Some studies chose reference close to the work being done [7, 23] or the choice of a reference was not mentioned, or not used at all [6, 18]; another [25] chose the opposite lower limb as was done in this study. One study that used needle insertion as electrodes and a similar signal propagation method as is done in this research chose to use a surface electrode as ground reference [8]; because of the capacitive affect of the skin, the potential at a point on the skin could be significantly different than the potential 1 cm below the skin in the tissue (which is the area of interest for this research) hence the reference point for the research of this thesis is inserted into the tissue.

During development in this research, it was found that choosing a point on the opposite lower leg produced a lower noise floor and less 60 Hz pickup than a point adjacent to the testing points on the arm. As can be seen in table 1, the noise floor is lower and the amplitude of the largest peak artifact is lowest for the leg reference. Hence a reference point was chosen and needled on the opposite lower leg from the arm being studied in a place where there is no acupuncture meridian. For consistency the point was chosen – in the inferior-superior direction – halfway between the meeting point of the bellies of the gastrocnemius and the posterior popliteal crease, and – in the medial-lateral direction – halfway between the middle of the gastroc and the lateral point on the leg. This reference point is grounded at the DAQ, in which effectively makes the local tissue at this point 0V, and all signals measured are referenced to this potential. This also
implies that when a signal is applied somewhere in the body, and there is no other connection on the body to building ground, the current will find the path of “least resistance” to this point.

The following data is from an acquire-only test (no electrical stimulation) to evaluate the noise floor to identify the best reference location, comparing the noise response of an inserted arm reference point with an inserted leg reference point.

<table>
<thead>
<tr>
<th>Noise floor</th>
<th>L111(dBv) arm ref.</th>
<th>L111(dBv) leg ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-98</td>
<td>-118</td>
</tr>
<tr>
<td>Largest spike</td>
<td>-46 (60Hz)</td>
<td>-101 (30Hz)</td>
</tr>
</tbody>
</table>

Table 1: Comparing noise at L111 with leg reference and arm reference

**Limitations of the Hardware and Measurements**

The accuracy of the measurements could have been improved with a higher resolution setting on the DAQ. Also the DC response of the DAQ was inconsistent. A better resolution could have been implemented with a software modification using the existing setup, but to improve the DC response of the DAQ, a different hardware configuration needed to be used.

The depth of the insertion of the needle, typically 10mm was determined from the experience of the researcher; yet in Ahn [2] ultrasound was used to ensure the point selection was in the connective tissue planes as well as the appropriate insertion depth. This could possibly have caused some measurement inconsistencies between participants.
To make participation easier for some people, testing was done at their place of work or at a local acupuncturist's office; 12 of the 20 were tested in Kingsbury Hall at UNH. Although there was no clear correlation between the results of the participants at Kingsbury hall and outside, it may have been better to test all in the same place.

**Study Method**

The study protocol was designed to test the hypothesis that a pulse will flow through acupuncture meridians in a manner that is different from a control channel, with a simple, repeatable, yet flexible configuration. Repeatable testing was used for statistical benefit; collecting ten, 500ms time intervals of acquisition with averaging produced a more reliable data. All acquisitions were logged directly to the hard disk and then later loaded, analyzed and measured for graphical and statistical analysis.

The study protocol was performed on 20 people (see Results chapter for results). The participants had no severe chronic health problems and they were between 20 and 60 years of age. For 12 of these people data was taken at UNH, Kingsbury Hall; the other 8 were evaluated at other locations, always inside. Ten of the participants had received acupuncture previously and 10 had not. The Institutional Review Board at the University of New Hampshire approved the study methods and accepted the use of human subjects (see Appendix A). The Test configuration and Point selection were discussed above in previous sections. The study participant was seated with the test arm resting on a table; the wrist was turned as in fig. 3 to ensure the trajectory through the tissue is uniform and to keep the same length for the LI and Ctr channel throughout the study. The
protocol for the full test is as follows (for reference see fig. 1).

a. Explain the study to the participant, talk about acupuncture, and demo needle insertion.

b. Insert 32 AWG needles into Leg Ref, LI11, CtrB, LI4S, and CtrS.

c. Stimulate LI4S and CtrB for up to 1 minute or before if the participant claims strong reaction (soreness, aching, pain etc.)

d. Apply 400μs, 500mV Gaussian pulse in a 500ms window to LI4S, acquire at LI11, repeat 10 times.

e. Apply 400μs, 500mV Gaussian pulse in a 500ms window to LI4S, acquire at CtrB, repeat 10 times.

f. Apply 400μs, 500mV Gaussian pulse in a 500ms window to CtrS, acquire at CtrB, repeat 10 times.

g. Apply 400μs, 500mV Gaussian pulse in a 500ms window to CtrS, acquire at LI11, repeat 10 times.

h. Remove all needles, study complete.

Data Analysis Methods

Most of this chapter addresses how the data is acquired: a signal is emitted into the tissue and picked up at particular points. At those points the ionic currents induce a potential at the point, and that current is what is measured at the receiving point. However potential is not always the best measurement for illustration purposes, particularly since we are concerned with the frequency response primarily. Hence the
main methods of analysis are DFT, spectral analysis, and power spectral density averaging.

For this thesis, fig. 4 shows the conceptual system for the following analysis.

![System for analysis and variable allocation](image)

**Fig. 4:** System for analysis and variable allocation

1. A typical DFT is given below,

\[ Y(k) = \sum_{n=0}^{N-1} y(n) \exp\left(-\frac{2\pi kn}{N}\right) \]

\( k = 0, 1, 2 \ldots N-1 \)

Measurements are given in:

\[ dBv = 20 \log \frac{2Afft}{N} \]

\( Afft = \) Amplitude output from the fft

\( N = 62500 \)

2. The spectral analysis for output/input is,
H(f)(dB) = Y(f)/X(f)

Through the thesis the points are sometimes used to define the signals hence,

\[ Y(k)/X(k) = \frac{\text{LI11/LI4S}}{\text{}} \]

Measurements are given in

\[ \text{dB} = 20\log Y(f)/X(f) \]

3. Power spectral density and total power

At LI11, a series of ten 500ms sequences are acquired. To best analyze from a data perspective and to get a number to do statistical analysis, periodogram type power spectral density averaging is used. For a deterministic process and a stochastic process the power spectral density gives the power of a signal; this process works well for this thesis since we have a signal at that point, and using the PSD, the input signal is not needed as in the spectral analysis.

\[ P_{xx} = \frac{1}{N} |Y(k)|^2 \]

Where \( Y(k) \) is the DFT of \( y(n) \).

\( P_{xx} \) is the PSD with units (W/Hz). The total power is the product of the PSD at each frequency multiplied by bin size (which is 1 Hz). This gives a single data value that can be used in statistical analysis.

\[ P(W) = \sum_{k=2}^{100} P_{xx}(k) \times 1Hz \]
4. Statistical analysis

To test the null hypothesis, a paired, two sided signed rank test was used. This is a difference test of null hypothesis that data in vector $x - y$ come from a continuous distribution with a zero median. An important factor choosing this test is that there is no need to have normal distribution. If the data from two tests $(x,y)$ are expected to be the same, then the median $x - y$ is expected to be zero; with a difference a certain $p$ value is given and if the $p < 0.05$, then a statistical significance is stated as is commonly done in research.
CHAPTER II

RESULTS AND DISCUSSION

To determine whether the ELF response was different on an acupuncture channel compared to a control channel, a study was performed on 20 people as described in the method chapter. The study was designed to measure the ELF response of acupuncture meridians compared to non-meridians, but it also yielded information about propagation of a Gaussian signal through an acupuncture meridian compared to off as well as estimating the velocity of propagation in the time domain.

The results of this thesis are presented two ways (for a detailed analysis discussion see the method section): graphically as a spectral analysis and through numerical data using power spectral density and total power calculations. It should be known that graphical results are thought provoking and illustrative but do not prove a statistical significance and hence give no information about the chance of randomness of the data.

Time domain power calculations

Before the presentation of the ELF data, total power from the time domain signal is presented for comparison. For each of the 20 participants, the total power in the pulse in the time domain was calculated for the LI meridian and compared to the Ctr channel. This was calculated by looking at just the time domain pulse response (a 560μs window) and not the whole 500ms sequence, effectively integrating over the size of the pulse:
\[ P_t(w) = \sum V_i^2 \cdot \Delta t \]

\[ V_i = \text{the value of voltage at each sample} \]

\[ \Delta t = 8 \mu s, \text{the time of one sample} \]

<table>
<thead>
<tr>
<th>Participant</th>
<th>Total Power ((\mu)w)</th>
<th>Total Power ((\mu)w)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LI</td>
<td>Ctr</td>
</tr>
<tr>
<td>1</td>
<td>20.52</td>
<td>20.34</td>
</tr>
<tr>
<td>2</td>
<td>23.23</td>
<td>16.89</td>
</tr>
<tr>
<td>3</td>
<td>15.46</td>
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<td>15</td>
<td>18.10</td>
<td>18.00</td>
</tr>
<tr>
<td>16</td>
<td>30.85</td>
<td>25.54</td>
</tr>
<tr>
<td>17</td>
<td>38.94</td>
<td>26.58</td>
</tr>
<tr>
<td>18</td>
<td>27.73</td>
<td>24.11</td>
</tr>
<tr>
<td>19</td>
<td>33.29</td>
<td>33.17</td>
</tr>
<tr>
<td>20</td>
<td>22.55</td>
<td>15.93</td>
</tr>
<tr>
<td>----</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Mean (Std)</td>
<td>26.69(7.86)</td>
<td>22.47(5.43)</td>
</tr>
</tbody>
</table>

**Table 2: Time domain power calculations**

**Discussion**

The area of interest in this research is the frequency range 2 – 100 Hz, yet a time domain power measurement, effectively measuring all the power in the pulse in the time domain shows a similar trend to the data found in the 2 – 100 Hz data (data in next section). Using the paired, two-sided signed rank test on the above data produces a $p = 0.027$, showing that there is a trend towards a difference along the acupuncture meridians as compared to the control channel; along the acupuncture meridian there was a higher power at the acupuncture measurement point compared to the control measurement point.

**ELF response of L1 channel compared to control**

**Hypothesis:** ELF signals propagate significantly better along acupuncture meridians when compared with non-meridian tissues.

This research followed the work of Langevin [1] and Ahn [2] by starting with the above hypothesis and investigated the tissues of meridians using a signal method and frequency response, an area lacking in the acupuncture research.

Characterizing an unknown system by analyzing the frequency response is a common method in electrical engineering, particularly with the ease of finding the Fourier transform with FFTs in signal processing software. Swept sinusoids and wide frequency pulse stimulation are two commonly used methods of stimulation. In acupuncture
research, the frequency response of points and channels have been investigated [8, 14, 15, 33] although there may have not been a control, or the measurements were made on the skin, or the reference was not appropriately chosen. Yet results from the studies have been clear: human tissue responds differently to the ELF range compared to higher frequency. A link to the Schuman resonances have been studied [14, 16] as well as the general low pass response with attenuation starting at about 20 Hz [8].

Method

A detailed discussion of the method, as well as the math behind the calculations, can be found in the Test Configuration and Developing and Validating the Method chapter. To test the frequency response of a system, apply a wide spectrum pulse which covers the frequencies of interest, perform the measurement at the point of interest and take the transfer function of output divided by input to find the response of the system. This test is no different. The level of the pulse is chosen large enough (0.5V) so the received signal is well above the noise floor of the test setup.

Results

The total power in 2 – 100 Hz of the signal measured at LI11 and CtrB are compared in table 3.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Total Power (µW) LI</th>
<th>Total Power (µW) Ctr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>5.88</td>
</tr>
<tr>
<td>2</td>
<td>4.96</td>
<td>4.68</td>
</tr>
</tbody>
</table>
Table 3: Total power in 2 – 100 Hz at LI11 and CtrB

<table>
<thead>
<tr>
<th></th>
<th>Median (Std)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.32</td>
<td>2.84</td>
</tr>
<tr>
<td>4</td>
<td>4.35</td>
<td>4.67</td>
</tr>
<tr>
<td>5</td>
<td>4.54</td>
<td>3.75</td>
</tr>
<tr>
<td>6</td>
<td>3.30</td>
<td>4.01</td>
</tr>
<tr>
<td>7</td>
<td>6.32</td>
<td>5.65</td>
</tr>
<tr>
<td>8</td>
<td>5.90</td>
<td>3.71</td>
</tr>
<tr>
<td>9</td>
<td>3.87</td>
<td>2.21</td>
</tr>
<tr>
<td>10</td>
<td>3.40</td>
<td>2.52</td>
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<tr>
<td>11</td>
<td>3.11</td>
<td>3.18</td>
</tr>
<tr>
<td>12</td>
<td>5.14</td>
<td>4.28</td>
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<td>13</td>
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<td>5.69</td>
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<tr>
<td>14</td>
<td>3.57</td>
<td>2.81</td>
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<tr>
<td>15</td>
<td>6.21</td>
<td>3.96</td>
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<td>4.65</td>
<td>3.72</td>
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<td>3.89</td>
<td>2.24</td>
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<tr>
<td>18</td>
<td>4.85</td>
<td>4.83</td>
</tr>
<tr>
<td>19</td>
<td>4.04</td>
<td>4.50</td>
</tr>
<tr>
<td>20</td>
<td>3.56</td>
<td>3.24</td>
</tr>
</tbody>
</table>

*Table 3: Total power in 2 – 100 Hz at LI11 and CtrB*

*Spectral Analysis of LI11/LI4S and CtrB/CtrS for four participants*

Plots of received signal as a function of frequency are shown below.
Fig. 5: The channel spectral response of 4 study participants from a Gaussian pulse stimulation, normalized to pulse amplitude

Discussion

A paired, two-sided signed rank test was performed on the data pairs of Table 3. The paired, two-sided signed rank test is appropriate for small sample sizes, and it does not require that the data be normally distributed. If the on-meridian, off-meridian data pairs were identical, the paired, two sided signed rank test would return a probability (p) of 1; the value of p gets smaller as the pairs become more dissimilar. For the data pairs in
Table 3, p=0.035 which indicates that the pairs are dissimilar, which suggests that the hypothesis proposed is correct. However, examination of the data in table 3 shows that in some cases the on-meridian signal is stronger while in others the off-meridian signal is stronger. This observation is inconsistent with the hypothesized assumption that meridians would be better conveyors of ELF electrical signals than non-meridian tissues. Hence, these data show that the hypothesis proposed is inconclusive.

The graphs of fig. 5 show what is statistically analyzed in table 3, the level of signal propagated in the LI meridian is, on average, greater than in the Ctr channel. It is also interesting to note the small differences in shape between people as well as the levels: some people have a lower response at earlier frequencies and increases with frequency and others show a decreasing response with frequency. Also the levels vary significantly from person to person – and also with the same person at different times which can be seen in table 3. Perhaps this spectral response can be used as an indicator of channel response and hence health of the person; it would be interesting for acupuncturists to take the graphical and analytical response of channels when patients first visit and compare as treatment progresses. In fig. 5, four participants with obviously greater signal response on channel are shown, but as can be seen in table 3, this is not the case for all the participants and similar plots can be shown with the signal response off the channel greater than on the channel for a few participants. Again this highlights a trend in the data but definitive results are inconclusive.
Pericardium Test

A pericardium test was included to find the characteristics of another acupuncture meridian, the pericardium (PC) compared to control, and also to compare results to Ahn [2], who found a statistically significantly lower impedance on a small section of the pericardium channel. The test method was the same as the LI test, except that the signal was launched on PC6, and detected at PC3; the control channel was 0.8mm medial and parallel (as done in [2]). The test was performed on four participants, three had consecutive tests. The total power results are in table 4, and the transfer function of two participants is in fig 6.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Total Power (µW)</th>
<th>Total Power (µW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC</td>
<td>Ctrl</td>
</tr>
<tr>
<td>1 (5/2-1)</td>
<td>3.46</td>
<td>0.494</td>
</tr>
<tr>
<td>1 (5/2-2)</td>
<td>3.77</td>
<td>0.493</td>
</tr>
<tr>
<td>2 (5/1)</td>
<td>2.07</td>
<td>2.43</td>
</tr>
<tr>
<td>3 (5/3-1)</td>
<td>3.49</td>
<td>4.08</td>
</tr>
<tr>
<td>3 (5/3-2)</td>
<td>3.53</td>
<td>4.12</td>
</tr>
<tr>
<td>4 (5/3-1)</td>
<td>4.52</td>
<td>4.51</td>
</tr>
<tr>
<td>4 (5/3-2)</td>
<td>4.57</td>
<td>4.53</td>
</tr>
<tr>
<td>5 (5/3-1)</td>
<td>4.70</td>
<td>4.28</td>
</tr>
<tr>
<td>5 (5/3-2)</td>
<td>4.62</td>
<td>4.29</td>
</tr>
</tbody>
</table>

Table 4: Total power in 2 – 100 Hz at PC3 and Ctrl
Fig. 6: Pulse spectral response of Pericardium and control for two participants

Discussion

The results of table 4 are similar to the results seen in the LI meridian. There may be a trend showing that the signal propagation along the meridian is higher than the control but the difference is not significant. Of course the sample for the pericardium test is too small to make any presumptions; all results could be random events. There is also another interesting point: the range of total power is 3.5 – 4.6 μW which is much smaller than the 1.3 – 7.4 μW of the LI channel. This observation may be due to the small number of individuals tested, but could also be a phenomenon of the PC6 and the pericardium channel.
CHAPTER III

DEVELOPING AND VALIDATING THE METHOD

The tests of the measurement equipment given in this chapter are given to validate that the data collected are correct, and are not contaminated by some artifact of the measurement process. Figure 7 shows the positive and negative inputs of the DAQ grounded; this effectively defines the noise floor for the system and that corresponds to the noise floor of fig. 9 ( > 4000Hz), the signal after the pulse falls off.

![Fig. 7: Positive and negative inputs grounded](image-url)
Gaussian Pulse Development

In the method of this thesis, a pulse was supplied: a 400μs, 500mV Gaussian pulse in a 500ms window, which was repeated 10 times. The aim was to detect the frequency response of the acupuncture points and meridians, but other measurements and characteristics of the tissue were determined and are presented in Chapter II (Results and Discussion).

Fig. 8: Time domain response of Gaussian pulse at LI8 and LI11
Fig. 9: Pulse response through tissue and resistor, normalized to their DC values

Fig. 8 shows the time domain response of the tissue with the Gaussian pulse stimulation; fig. 9 compares the frequency response of the tissue with a known response through a resistor; the shape is very similar. Fig. 9 also conveys the point that the signals measured are 40dB above the noise floor. Since the aim was to test the ELF response of the acupuncture meridian with the pulse stimulus, it was important to have as little rolloff as possible in the frequencies of interest; making the pulse more narrow, would increase the frequency response, but would decrease the amplitude, moving the signal closer to the noise floor. The amplitude was set to 0.5V since a 1 V pulse (applied to LI4) caused the nerve to be stimulated and pulsed the abductor pollicus muscle, which was uncomfortable. The Gaussian pulse was also tested on a simple resistor divider network to ensure that the system would show an attenuation, which it did as expected. The width of the pulse chosen gave less than 1dB rolloff at 500 Hz.
Repeatability

Repeatability was tested to ensure consistency of the test method and to produce results that may be significant for the research. For each person receiving the full test session, the pulse is emitted 10 times into the tissue (to perform an averaging). Fig. 10-13 shows the spectral response of all 10 sequences for two participants of the study (one is the main outlier) to show the consistency of the measurement.

Fig. 10: Spectral response of LI11/LI4S, one person all 10 sequences
Fig. 11: Spectral response LI11/LI4S, figure 10 measurements averaged

Fig. 12: Spectral response LI11/LI4S, outlier all 10 sequences
Fig. 13: Spectral response LI11/LI4S, figure 12 measurements averaged

Fig. 14 shows the variation between 12 participants from the study data; this is averaged transfer function. As can be seen one participant is an outlier (sequences shown above in fig. 12, 13).

Fig. 14: Pulse Spectral Response LI11/LI4S for 14 participants

The plot of fig. 14 was included to illustrate the variation among the participants and to show consistency of the test configuration. With a common scale, it can be seen that some graphs are flat, some increase slightly, and some decrease slightly. With this scale it
is seen that the variation in shape is actually very little, but the variation in amplitude corresponds with the variation seen in the total power value.

Participants were tested for repeatability for numerous testing sessions; four were tested two sessions in a row. To compare the results between consecutive sessions and sessions days or weeks apart, total power was calculated (see table 5).

<table>
<thead>
<tr>
<th>Part. # (date)</th>
<th>Total Power L111 (µW)</th>
<th>Total Power CtrB (µW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 (4/23)</td>
<td>4.93</td>
<td>4.95</td>
</tr>
<tr>
<td>15 (4/25-1)</td>
<td>3.53</td>
<td>5.22</td>
</tr>
<tr>
<td>15 (4/25-2)</td>
<td>3.54</td>
<td>5.11</td>
</tr>
<tr>
<td>15 (4/27-1)</td>
<td>3.56</td>
<td>3.24</td>
</tr>
<tr>
<td>15 (4/27-1)</td>
<td>3.40</td>
<td>3.10</td>
</tr>
<tr>
<td>13 (3/26)</td>
<td>7.98</td>
<td>5.69</td>
</tr>
<tr>
<td>13 (4/25-1)</td>
<td>5.47</td>
<td>1.97</td>
</tr>
<tr>
<td>13 (4/25-2)</td>
<td>5.03</td>
<td>1.97</td>
</tr>
<tr>
<td>14 (4/25)</td>
<td>6.21</td>
<td>3.96</td>
</tr>
<tr>
<td>14 (3/26)</td>
<td>7.41</td>
<td>6.18</td>
</tr>
<tr>
<td>2 (3/7)</td>
<td>4.96</td>
<td>4.68</td>
</tr>
<tr>
<td>2 (4/23)</td>
<td>3.57</td>
<td>2.81</td>
</tr>
<tr>
<td>19 (4/26-1)</td>
<td>4.04</td>
<td>4.49</td>
</tr>
<tr>
<td>19 (4/26-2)</td>
<td>4.73</td>
<td>5.05</td>
</tr>
</tbody>
</table>

Table 5: Total power measurement from repeatability testing
Two important points can be seen: when the sessions were consecutive, the LI and Ctr total power were similar; when the sessions were at least one day apart either the LI, the Ctr, or both of the total power measurements changed significantly.

To test the consistency of the acquisitions in the time domain, all 10 pulse sequences of 1 session were overlaid on one graph as shown in fig. 15. The point of fig. 15 is to show that the time domain pulse response of the tissue is consistent and repeatable over the 500 ms interval. Importantly, this demonstrates that the introduction of the pulses does not change the channel propagation characteristics.

![Pulse time domain response in tissue, 10 seq., synchronized](image)

**Fig. 15:** Pulse time domain response, 10 sequences, synchronized
**Full Test on Chicken Tissue**

To further investigate the test configuration in vitro, the full test was performed on a chicken a number of times; an organic chicken breast purchased at the local grocery store was used as the sample both times. The description of cold, dead chicken defines the setup that a live chicken, or warm tissue, may have a different response. The pulse ELF frequency response is shown in fig. 16, and the pulse time domain response is fig. 17.

![Pulse transfer function (o/p/i/p) of a cold, dead, chicken](image)

**Fig. 16:** Pulse spectral response (o/p/i/p) of a cold, dead, chicken
The pulse spectral response of the chicken (fig. 18) has little variation with frequency, there is no shape to the transfer function seen in the human tissue which occurred in nearly all of the study participants. Many weeks later another chicken was tested repeatedly over a two day period. The ELF response is shown in fig. 18, measuring signal level at the needle electrode. There are two groupings, one grouping is from one set of
electrodes, and the other grouping is from another set of electrodes. Even though the
distance was the same between the two sets of needles, the response was a couple dB off.
The most important point is the consistency within each grouping over different times,
even different days. The 30 Hz peak is an artifact not occurring in the pulse frequency
response in human. And lastly the shape of the pulse propagated in the time domain
remains a similar Gaussian shape as input to the chicken
CHAPTER IV

THE IDIOSYNCHRANIES OF PERFORMING ELECTRICAL TESTS ON BIOLOGICAL TISSUE

Electrode Polarization

"Electrode Polarization is a major nuisance," [27] begins a paper of H.P. Schwan, a pioneer in electrical characterization of biological tissue, who has been studying the phenomenon of polarization since the 1960's; it is an important phenomenon to consider when any electrical measurements are made on biological tissue. When an electrical stimulus is applied to biological tissue (or any ionic concentration) there is a polarization of the ions around the electrode surface causing an electrical double layer that will modify the signal and hence affect any measurement taken on the tissue, see fig 19. In biological tissue, a relatively continuous ionic concentration in the tissue, of both positive (K, Na) and negative (Cl) ions before the electrical stimulation, becomes a local well of ionic charge forming a bilayer that diminishes with distance. This is commonly modeled by a series resistor and series capacitor [28],

\[ Z_p = R_p + \frac{1}{j\omega C_p} \]

Unfortunately the effect is highly variable and cannot be easily compensated, but efforts are made for correction.
The magnitude of this impedance, called contact impedance, can be so large, that correcting for it has been a major direction in biological research [12,13, 28-30]. Some of the methods are four-electrode setups, distance variation, substitution methods, special electrode preparation, and high current density [30]. As with a lumped series capacitor, the impedance is greater at low frequencies, and more of a concern when taking impedance measurements (in physiological saline solution $C_p = 2\mu F$ at 10kHz and $C_p = 11\mu F$ at 100kHz) [28]; consistent DC measurements can prove difficult. Also there is a non-linearity at low currents; for small AC current density (< 1mA) there is little change in $R_p$ and $C_p$, and it increases with increasing current. Hence this is the reason some researchers choose a high frequency, low current signal as a source for making measurements on biological tissue. Yet for this research, ELF frequencies less than 100 Hz are the primary concern, but low currents are used and impedance is not the major parameter of measurement.
Impedance Measurements vs. Signal Propagation

When measuring biological tissue electrical response, impedance is commonly the parameter of choice. With Biological Impedance Analysis (BIA), equations can be formulated to calculate body cell mass (BCM), fat free mass (FFM), and total body water (TBW). By holding a portable unit with two hands, these measurements can quickly be displayed. Most importantly impedance can be easily modeled using lumped components. The standard model of the electrical properties of the skin is a resistor in series with a shunt component of resistor and capacitor. For the measurements presented in this thesis, the measurements are made in the muscle and connective tissue, so a skin model is not sufficient. Much of the work for modeling ionic currents in biological tissue has been done considering cell membranes and the ionic change over the cell membrane with potentials applied. The model for the current through the cell membrane was determined by Hodgkin [11]:

![Electrical circuit model of cell membrane](image)

**Fig. 20:** Electrical circuit model of cell membrane

With appropriate models, simulation and testing can be performed on the desktop instead of in the difficult setting of experimental procedures; results are then predictable
and reproducible. Yet, as is discussed below in ionic currents section, ionic currents of low frequencies propagate predominantly around the cells, through the extracellular volume rather than through the intracellular volume.

When considering measuring acupuncture points and channels, impedance has been a common measurement particularly measurements made on the skin. When thinking of the system in terms of lumped parameters, this seems a likely choice. If acupuncture meridians are suppose to transmit information better than other pathways, then it is likely a path of least resistance, hence it seems like a good idea to push a current thru the tissue and measure the impedance through that path. But, unfortunately, biological tissue is not best modeled by lumped components [12, 22] and a different conceptual model is needed. Ahn lists the properties of biological tissues why they do not fit well in the lumped component model [12]:

1. Ionic currents: in biologic tissue the current is transferred by charged ions, not electrons as in conductors.

2. Complexity: Biologic tissues contain complex materials that may produce a sudden discontinuity in current path, soon followed by a frequency dependent material, neither of which may be suited to a resistive, capacitive, or inductive modeling.

3. Nonlinearity: tissues can exhibit nonlinear behavior with respect to amplitude, frequency, even direction.

4. Open systems: Living biological organisms are open systems with parameters that will vary; for example emotion, perspiration, movement, and respiration can dramatically affect electrodermal measurements.
Instead of using impedance measurements, the signal propagation model is proposed as a superior means to measure the electrical activity of biological tissue in vivo. When using the impedance measurement, current is injected at one point and retrieved at another point by making that point a least resistive pathway; with the signal propagation method you emit a signal one point allowing it to propagate through the tissue and pick a point to measure with a high impedance probe which will not affect the propagation significantly. The signal propagation method, which would include applying a constant voltage source, rather than a current source, has been done before in acupuncture research [8, 15, 23], but the methods are vague and the data was presented vaguely rather than with a statistical analysis.

Also the intention of this thesis is to measure the ELF frequency response of acupuncture channels; testing frequency with a wide spectrum pulse is a common method in electrical engineering, leading to the analyses used in this study – transfer function and power spectral density averaging – which are well suited to the signal propagation method.

**Ionic Currents through Biological Tissue**

As mentioned previously one method of test setup to compensate for electrode polarization, particularly with impedance measurements, is the four-electrode measurement, and this method is used in numerous acupuncture studies [2, 9, 26]. Yet Grimnes undertook an investigation into different methods and concluded, “it is nevertheless a fact that tetrapolar systems are more vulnerable to errors than monopolar
or bipolar systems.” [13] A better test setup would be to consider how the biological tissue reacts.

When an electrical source is applied to biological tissue, the current will propagate in all directions as if you are emitting a signal from an antenna in an ionic medium; the current density through the tissue will propagate in the path of least resistance towards the ground, in this case towards Leg Ref. The current does not propagate along nicely as through a resistor, or waveguide, or transmission line, the current propagates through an inhomogeneous medium (see fig. 21). Active tissues are involved, and current passes through many parts of the body, not just in a nice straight line [22]. And to complicate matters more, ionic current propagation through biological tissue depends on frequency.

![Fig. 21: Propagation of ionic current through biological tissue](image)

There are three dispersion regions identified for current propagation through soft tissue: $\alpha$, $\beta$, and $\gamma$ associated with low, radio, and microwave frequencies [31]. For the lower frequencies, ionic currents tend to propagate around cells, in the extracellular space as cell membranes act as a capacitive impedance: higher at lower frequencies. As frequencies increase the membrane impedance decreases, hence current propagates through the intercellular space. Facial convergences around muscle bundles for example,
are great planes of extracellular space, hence the ionic current will have a greater
tendency to propagate along these planes.

A commonly used model for electrical conduction through biological tissue for
frequency domain analysis is a series configuration of a shunt capacitor and resistor, see
fig. 22 [19].

![Lumped component tissue model for frequency domain analysis](image)

**Fig. 22**: Lumped component tissue model for frequency domain analysis

Although this is nice and simple to use, from the graphical results of this thesis using the
signal propagation method (see fig. B 23 ) the propagation of the signal for frequencies
less than 50 Hz produce very little attenuation with distance, and the attenuation increases
for higher frequencies (measured up to 500Hz).

**Effect from the Skin**

As mentioned in the introduction, most of the acupuncture research is carried out on the
skin, which is curious since acupuncture uses needles and requires a puncturing of the
protective, highly resistive and capacitive layer that is the skin. The impedance
measurements on the skin will depend greatly on the layer of the dermis you are testing
[32]; for example you will measure a significant difference in impedance – current will
differ – if you use a surface electrode compared to a probe with a needle that may be

46
breaking some of the layers of the dermis. Hence the efficacy of the common measuring tools that measure the impedance on the skin with an electrode point will give varying measurements depending on how deep you press [33]. For this method this is not a problem as the electrodes are needles inserted into tissue. Even the ground reference point (Leg Ref) is inserted into the tissue, effectively setting the local area around the needle to 0V.
A significant body of research has been performed to investigate the anatomic-physiological means of acupuncture as well as to study acupuncture from an electrical perspective. When investigating the acupuncture points and meridians, an unusually large amount of research focuses on the skin; this is unusual since the meridians from a Chinese acupuncture theory run in the tissue as well as the education from a Traditional Chinese Medicine (TCM) perspective instructs insertion of most points about 1 cm deep. In this thesis, the model followed is the connective tissue model, saying that the meridians follow the connective tissue planes through the body, often within muscle bundles. Following acupuncture theory, using electrical engineering tools, and applying biological science, a method to test the ELF response of acupuncture meridians and points was introduced, analyzed, validated and tested with a small study. With this study the total power of the signal in the 2 – 100 Hz range at a particular point on the LI meridian with a pulse applied distally on the meridian was compared to the total power of the signal on a control point with a pulse applied distally. That total power was shown to be statistically significantly greater for the LI meridian but with a p = 0.035, the data can be said to be merely a trend rather than a dramatic difference as expected.

With this thesis, the results that support or disprove the hypothesis follow from experimental investigation and statistical analysis; hence the test configuration is crucial with a flexible yet powerful Matlab based platform using a DAQ with high impedance
input instrumentation amplifiers. Considerable time was spent testing the hardware and these results were presented in the thesis as well; for numerous participants of the study there were repeatability studies where they were tested either consecutively or after days or weeks. Surprisingly if the tests were done consecutively then the total power measurements were consistent with the test just done previously, but after one or more days then there was no consistency only following the general trend. There is too little data to say much about this phenomenon but is this variation due to diurnal changes, emotional changes, stress levels?

Also, for a small group of people (5), the Pericardium meridian was tested using the same method as for the LI meridian. Again the results were not dramatic, for the small group there was a trend showing a better signal propagation through the Pericardium meridian compared to the control but not greatly (this trend is even less certain because of the small sample of people). Also with the few people the actual total power on the channel varied less than the LI meridian.

Results of the test of the meridians were graphically shown as spectral response or numerically as total power in the 2 – 100 Hz range. There may be more here than just signal propagation. For the LI testing there was a difference, although inconclusive, in the level of total power as well as their spectral response. Some people had the total power in the control channel higher as well as a different shape spectral response; assuming that these variations were real and not inconsistencies in the test method, a more formal questionnaire may be indicated requesting the current health of the person (tired, stressed, sleep levels, hunger etc.) with correlations towards the meridians being tested. This may provide more information about the variations. For future studies, other channels can be
analyzed the same way, finding a norm, and then this value as well as the spectral response can be seen as a state of health, and a state of the acupuncture meridian that can be used by an acupuncturist. Also as the meridian “clears” with acupuncture treatment, this method can be used not only as a diagnostic tool but also as monitoring the state of the channel with treatment.

The ELF range was chosen since this is the region of EKGs, EMGs, and EEGs, as well as electrical controlling systems hypothesized in the literature. Yet the results of this research show a trend towards better propagation of ELF signals through acupuncture channels compared to a control but not as dramatic as expected. From some of the results of other studies, a model of significantly greater transmission – like the propagation in a transmission line compared to outside the line – along the acupuncture meridians are proposed. This research does not support this. Hence if there is only a trend towards the acupuncture meridians then that says there is either another means of implementation for acupuncture beside electrical activity, or the control is also active and the comparison is not a transmission line with an inactive substrate but an active substrate (control channel) with a more active substrate (acupuncture meridian).
CHAPTER VI

FUTURE WORK

The results of this thesis show a trend for a larger total power in the 2-100Hz band being transmitted from along a section of the LI channel compared to a control channel; the number of participants was 20. There is a temptation to say that a larger study should be undertaken to further determine this relationship, and this should be done to replicate the results here. But a better study would be to perform this test on other meridians of the body, perhaps one where the adjacent meridians are not so close (the bladder on the lower leg fits this description well). Many participants had strong reactions on the control source point with needle insertion and with needle stimulation as you would expect to see at an acupuncture point; again this points to an idea that there is activity not expected in the control.

Other future work stems from the results of the tests given in the appendix. To further test the phenomenon of unique spectral response at particular points, using the same Gaussian pulse stimulus setup, it would be informative to measure the different spectral response of numerous acupuncture points throughout the body and compare them to control points. This could be performed on a large number of people to begin a database of “normal” reaction of acupuncture points to compare to those that may be pathological. Then this may be used in health care settings to compare healthy points to points that may need acupuncture.
Using this setup, it would be interesting to see an acupuncturist measuring a particular channel through the progress of treatment. In acupuncture, the meridian is said to flow better with regular treatment, would the electrical characteristics consistency change?

In the development of the project, using an acquire only setup (no pulse stimulation), the ELF transfer function was seen to decrease with needle stimulation as well as a long time sampling (10 minutes) setup showed a change with needle stimulation. This was not pursued in this thesis because of the questions of the DAQ with these measurements, but if these results could be substantiated with op amps better designed for biological tissue, then these results could be dramatic.
REFERENCES


27. Schwan HP. Linear and non linear electrode polarization and biological materials. *Annals of Biomedical Engineering.* 1992; 20; 269-288


29. Feldman Y, Ermolina I, Hayashi Y. Time domain dielectric spectroscopy study of biological systems. *IEEE Transactions on Dielectrics and Electrical Insulation.* 2003; 10 (5); 728-753


33. Poon CS. Comments on “Laplace Plane Analysis of Transient Impedance Between Acupuncture Points LI4 and LI12”. *IEEE Transactions of Biomedical Engineering.* 1979; 26 (3); 181-182


APPENDIX A

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17-Oct-2007

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Electrical Engineering
3 Rainbow Drive
Dover, NH 03820

IRB #: 4086
Study: Electrical analysis of acupuncture channels
Approval Date: 10-Oct-2007

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved the protocol for your study as Expedited as described in Title 45, Code of Federal Regulations (CFR), Part 46, Subsection 110 with the following comment(s):

1. The researcher should remove the last sentence of #5 in the consent form as it is not necessary for this study.

Approval is granted to conduct your study as described in your protocol for one year from the approval date above. At the end of the approval date you will be asked to submit a report with regard to the involvement of human subjects in this study. If your study is still active, you may request an extension of IRB approval.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the attached document, Responsibilities of Directors of Research Studies Involving Human Subjects. (This document is also available at http://www.unh.edu/osr/compliance/irb.html.) Please read this document carefully before commencing your work involving human subjects.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or Julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

Julie F. Simpson
Manager

cc: File
    Chamberlin, Kent
APPENDIX B

RESULTS FROM OTHER RESEARCH

With an ELF Gaussian pulse stimulation, signals in the range <50Hz show less attenuation than greater frequencies which begin to show an increased attenuation with distance.

The lumped component tissue model [19] is shown in fig. 22. With this model you would expect greater attenuation with tissue length in the lower frequencies compared to the higher frequencies (due to the capacitor). The graphical results shown below do not follow this hypothesis for frequencies < 50 Hz.

Two plots are shown in fig. B 23 to illustrate the assertion.
Fig. B 23: Two participants pulse spectral response, LI11/LI4S and LI8/LI4S

Discussion

The important points to notice when considering fig. B 23 is not the different shape of the pulse frequency response of the two participants, but the fact that there is little attenuation in the < 50Hz range and then the attenuation with distance begins to become evident after that. These two are samples of similar response in all the participants. As you would expect, there is more attenuation for farther distance – LI11 is a farther propagation distance compared to LI8 – and the levels for LI8 are higher.

Another important point that came from this test is an understanding about ionic propagation. The values for the two graphs of fig. B 23 are about –6dB; if this was a circuit or a medium with attenuation (a dielectric) you would say that half of the signal was attenuated by the time it reached the electrode. That is not the case. LI8 and LI11 were 10cm apart, and LI8 was about 15 cm from LI4S. Since at the low frequencies there is very little attenuation between the two (and at higher frequencies a little attenuation), then the impedance model for signal propagation through tissue does not apply. If this
applied you would expect a definite, perhaps linear attenuation with distance. Here a better model is the signal emission model: the signal is emitted at a point, and the signal propagates optimally in a 3d manner around the point depending on the anatomical arrangement and locality of the point. The measurement at the test point is a lower amplitude, not because there was attenuation between the signal source and the input electrode, but because some of the energy of the signal is lost because of the propagation of the signal in other directions.

An electrically stimulated source point in the biological tissue produces an alteration of the spectral response, the shaping of the frequency response, not seen in tissue away from the point.

When first seeing the graph of the transfer function LI11/LI4S (fig. B 24), and thinking with the impedance model most commonly used in electrical engineering and the biological sciences when modeling tissue, you would expect the attenuation to be consistent over the length of the channel. That is, the response LI11/LI8 would have the same profile as LI11/LI4S with a variation in attenuation; this is not the case (see fig. B 24 and fig. B 25).
Discussion

This is saying that the main affect on the frequency response of the signal measured at the endpoint is not the tissue along the channel, but the *stimulation of the tissue around the needle*. This is perhaps due to the electrode polarization of the ions around the needle, which is an undesirable artifact in some measurements. But in these
measurements, the local ionic response that is stimulated from the applied pulse around
the acupuncture needle may be important reaction of that point, not an artifact to be
compensated; perhaps the ionic response around the point is unique to that point and may
change with location on the body as well as state of health of the person. From this
assertion the effect of the tissue away from the source point is negligible, most of the
effect comes locally from the tissue around the point. Using the same setup, it would be
interesting to measure the different spectral response of numerous acupuncture points.
APPENDIX C

CROSSTALK TEST

To ensure there was no crosstalk, particularly pickup over the long wires, a crosstalk test was performed following the lumped model of fig. C26. The same wires were used as in the study and $R_a = R_l = 1k$ ohm (estimating arm and leg impedance). The Gaussian pulse sequences are output into the circuit with the input op amp acquiring data at the same time. The results can be seen in fig. C27; the signal is in the noise floor and there is no sign of pickup of the pulse signal.

![Fig. C 26: Setup for crosstalk test](image-url)
Fig. C 27: Crosstalk test, signal at input