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Development of an Impedance-Controlled Hot Snare Polypectomy Device to Minimize Tissue Damage

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DEVELOPMENT OF AN IMPEDANCE-CONTROLLED HOT SNARE POLYPECTOMY DEVICE TO MINIMIZE TISSUE DAMAGE

by

CURTISLEE THORNTON

(Under the Direction of JungHun Choi)

ABSTRACT

This study explores the ability to measure the changing impedance, ex vivo, of a porcine colon sample while undergoing a high-frequency alternating current from an Olympus PSD-30 electrosurgical unit and stop the applied current before excessive tissue damage ensues. The causes of the thermal damage are first examined, followed by the construction and testing of the impedance-controlled feedback device. Perforation was observed to occur when the impedance of the tissue sample increased by 25% or more. Using this information, the device was tested for five power settings ranging from 10W-50W. In each trial, the feedback device stopped the applied current to the tissue samples when the measured impedance exceeded the cut-off threshold of a 25% increase from the starting impedance. The device was found to have an accuracy of ±5Ω. This successfully minimized undue tissue damage and proved able to prevent serious complications such as perforation from occurring.

INDEX WORDS: Polypectomy, Snare, Impedance, Feedback control, Radiofrequency ablation
DEVELOPMENT OF AN IMPEDANCE-CONTROLLED HOT SNARE POLYPECTOMY DEVICE TO MINIMIZE TISSUE DAMAGE

by

CURTISLEE THORNTON

B.S., Augusta University, 2015

A Thesis Submitted to the Graduate Faculty of Georgia Southern University in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

STATESBORO, GEORGIA
DEVELOPMENT OF AN IMPEDANCE-CONTROLLED HOT SNARE POLYPECTOMY DEVICE TO MINIMIZE TISSUE DAMAGE

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July 2019
DEDICATION

To my wife Julia.
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I would like to thank Dr. JungHun Choi for giving me the opportunity to work on this study with him and for giving me the push to make this happen. I would also like to thank Thomas Cannon for showing me the ropes around the lab.
TABLE OF CONTENTS

ACKNOWLEDGMENTS........................................................................................................3
LIST OF TABLES...............................................................................................................5
LIST OF FIGURES..........................................................................................................6
CHAPTER
1 LITERATURE REVIEW
   Reason for Study........................................................................................................7
   Colonoscopic Polypectomy.........................................................................................8
   Electrosurgical Unit..................................................................................................9
   Electrosurgical Unit Instruments...........................................................................10
   Radiofrequency Ablation.........................................................................................12
   Bioelectrical Impedance.........................................................................................13
   Bioelectrical Impedance Methods..........................................................................14
   Modeling..................................................................................................................15
   Current Pump..........................................................................................................16
   Objectives.................................................................................................................17
2 METHODS
   Devices.....................................................................................................................18
   Electrical Components..........................................................................................19
   Modified Electrosurgical Unit...............................................................................20
   Measuring System..................................................................................................21
   Control System.......................................................................................................23
   Operation................................................................................................................25
   Equivalent Circuit Preparation..............................................................................27
   Colon Sample Preparation......................................................................................28
3 RESULTS
   Current Pump..........................................................................................................29
   x2 Multipliers.........................................................................................................30
   Verification of Feedback System..........................................................................31
   Perforation Measurements.....................................................................................35
   Prefire vs Postfire Impedance...............................................................................37
   Impedance Over Time.............................................................................................51
4 DISCUSSION
   Feedback System....................................................................................................56
   Limitations...............................................................................................................58
   Similar Experiments...............................................................................................58
5 CONCLUSIONS
   Objectives.................................................................................................................59
   Closing Remarks......................................................................................................59
REFERENCES................................................................................................................61
APPENDICES
A. ARDUINO SKETCH USED TO CONTROL THE TIMING............................................67
B. MATLAB SCRIPT USED FOR DATA ANALYSIS....................................................71
C. LABVIEW VI FRONT PANEL AND BLOCK DIAGRAM......................................79
LIST OF TABLES

Table 3.1: Prefire vs postfire percent increase of impedance
..................................................................................50
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Example of Cole-Cole plot with a fitted line showing $R_0$ and $R_\infty$.</td>
<td>15</td>
</tr>
<tr>
<td>1.2</td>
<td>RRC equivalent circuit to mimic the human body.</td>
<td>16</td>
</tr>
<tr>
<td>2.1</td>
<td>Modified PSD-30 foot pedal assembly.</td>
<td>21</td>
</tr>
<tr>
<td>2.2</td>
<td>Voltage measurements for DAQ of the DUT and reference resistor.</td>
<td>23</td>
</tr>
<tr>
<td>2.3</td>
<td>Complete impedance-controlled feedback system.</td>
<td>25</td>
</tr>
<tr>
<td>2.4</td>
<td>Schematic diagram of the feedback system.</td>
<td>26</td>
</tr>
<tr>
<td>2.5</td>
<td>Porcine colon sample setup with snare.</td>
<td>28</td>
</tr>
<tr>
<td>3.1</td>
<td>Current pump test with the voltage drop across a $475\Omega$ resistor.</td>
<td>29</td>
</tr>
<tr>
<td>3.2</td>
<td>First amplifier with an ideal gain of two.</td>
<td>30</td>
</tr>
<tr>
<td>3.3</td>
<td>Second amplifier with an ideal gain of two.</td>
<td>31</td>
</tr>
<tr>
<td>3.4</td>
<td>500$\Omega$ cut-off threshold verification test.</td>
<td>32</td>
</tr>
<tr>
<td>3.5</td>
<td>750$\Omega$ cut-off threshold verification test.</td>
<td>33</td>
</tr>
<tr>
<td>3.6</td>
<td>1000$\Omega$ cut-off threshold verification test.</td>
<td>33</td>
</tr>
<tr>
<td>3.7</td>
<td>50W perforation test.</td>
<td>36</td>
</tr>
<tr>
<td>3.8</td>
<td>10W 1s prefire vs postfire Cole-Cole plot.</td>
<td>36</td>
</tr>
<tr>
<td>3.9</td>
<td>10W 2s prefire vs postfire Cole-Cole plot.</td>
<td>38</td>
</tr>
<tr>
<td>3.10</td>
<td>10W 3s prefire vs postfire Cole-Cole plot.</td>
<td>38</td>
</tr>
<tr>
<td>3.11</td>
<td>20W 1s prefire vs postfire Cole-Cole plot.</td>
<td>39</td>
</tr>
<tr>
<td>3.12</td>
<td>20W 2s prefire vs postfire Cole-Cole plot.</td>
<td>40</td>
</tr>
<tr>
<td>3.13</td>
<td>20W 3s prefire vs postfire Cole-Cole plot.</td>
<td>40</td>
</tr>
<tr>
<td>3.14</td>
<td>30W 1s prefire vs postfire Cole-Cole plot.</td>
<td>41</td>
</tr>
<tr>
<td>3.15</td>
<td>30W 2s prefire vs postfire Cole-Cole plot.</td>
<td>41</td>
</tr>
<tr>
<td>3.16</td>
<td>30W 3s prefire vs postfire Cole-Cole plot.</td>
<td>42</td>
</tr>
<tr>
<td>3.17</td>
<td>40W 1s prefire vs postfire Cole-Cole plot.</td>
<td>43</td>
</tr>
<tr>
<td>3.18</td>
<td>40W 2s prefire vs postfire Cole-Cole plot.</td>
<td>44</td>
</tr>
<tr>
<td>3.19</td>
<td>40W 3s prefire vs postfire Cole-Cole plot.</td>
<td>44</td>
</tr>
<tr>
<td>3.20</td>
<td>50W 1s prefire vs postfire Cole-Cole plot.</td>
<td>45</td>
</tr>
<tr>
<td>3.21</td>
<td>50W 2s prefire vs postfire Cole-Cole plot.</td>
<td>46</td>
</tr>
<tr>
<td>3.22</td>
<td>50W 3s prefire vs postfire Cole-Cole plot.</td>
<td>46</td>
</tr>
<tr>
<td>3.23</td>
<td>Prefire vs postfire percent increase of impedance for $R_0$.</td>
<td>47</td>
</tr>
<tr>
<td>3.24</td>
<td>Prefire vs postfire percent increase of impedance for $R_\infty$.</td>
<td>48</td>
</tr>
<tr>
<td>3.25</td>
<td>Prefire vs postfire percent increase of impedance at 50kHz.</td>
<td>49</td>
</tr>
<tr>
<td>3.26</td>
<td>10W firing test impedance over time.</td>
<td>52</td>
</tr>
<tr>
<td>3.27</td>
<td>20W firing test impedance over time.</td>
<td>53</td>
</tr>
<tr>
<td>3.28</td>
<td>30W firing test impedance over time.</td>
<td>53</td>
</tr>
<tr>
<td>3.29</td>
<td>40W firing test impedance over time.</td>
<td>54</td>
</tr>
<tr>
<td>3.30</td>
<td>50W firing test impedance over time.</td>
<td>55</td>
</tr>
</tbody>
</table>
CHAPTER 1

LITERATURE REVIEW

Reason for Study

In 2015 alone, there were 17.5 million cancer cases including 8.7 million deaths worldwide (Fitzmaurice et al. 2017). This places cancer as the second leading cause of death worldwide. This trend also carries over to the United States. In the same year, there were over 2.7 million total deaths, with cancer ranked second, contributing to 22% of the total (Siegel, Miller, and Jemal 2018). Of all the types of cancers, colorectal cancer was the fourth most commonly diagnosed cancer contributing to over 50,000 deaths each year (Wolf et al. 2018). The risk of developing colorectal cancer is 1 in 22 for men and 1 in 24 for women (Street 2019). Despite being the fourth highest killer, colorectal cancer has seen a steady decline in the incidence and mortality rates since the 1980s. This is in part contributed to the improvements in treatment as well as the increase in the number of screenings (Edwards et al. 2010). Screening for colon cancer is the number one way to identify precancerous polyps and increases the chances of a successful treatment plan due to early detection. The number of diagnosed are projected to increase because of a national campaign launched in 2014, Screen for Life, to increase the number of screenings in adults from 65.1% in 2012 to 80% by 2018 (CDC 2013).

The main avenue of approach for screening consists of a colonoscopy. When a polyp is found, polypectomy needs to take place. It was found that during the colonoscopy, the use of polypectomy has significantly reduced the incidence of and mortality from colorectal cancer (Anderloni et al. 2014). Although from this procedure, multiple complications can arise. Some of which include post-polypectomy coagulation syndrome, bleeding, and the most severe perforation. Although the rates for colorectal cancer have been decreasing for decades, the perforation and mortality rate has remained stable from 2001 to 2015 (Reumkens et al. 2016). This is alarming as perforation can cause severe post-surgery complications and even death. One study, of over 250,000
colonoscopies performed, showed a perforation rate of 0.07% (Iqbal et al. 2008). Another study of nearly 38,000 colonoscopies showed a perforation rate as high as 0.113%, with a mortality rate of 25.6% of those that underwent surgical intervention (Teoh et al. 2009). It was concluded by Panteris et al. that, “awareness and experience are the only preventative measures that can limit the incidence of perforation” (Panteris, Haringsma, and Kuipers 2009). If the experience of the surgeon is a major factor in the rate of post-polypectomy complications, then there needs to be a way to assist the surgeon further to continually improve the treatment for the patient. To accomplish this, we need to first investigate the methods used and the factors that contribute to the tissue damage. From this information, we can then design a device that will lower the need for an experienced surgeon. This will, in turn, reduce the number of complications and continue to lower the overall perforation and mortality rate.

**Colonoscopic Polypectomy**

Colonoscopic polypectomy is the removal of colorectal polyps. These polyps come in two types, sessile and pedunculated. Sessile polyps are flat while pedunculated polyps are taller and usually extend with a stalk from the inside of the colon wall. Sessile polyps are far more commonly found during the procedure. With a population size of 1620 lesions, 77% were sessile and 23% were pedunculated (Choo and Subhani 2012). These polyps are also classified by size. This includes diminutive for polyps less than 5 mm, small for polyps between 5 and 9 mm, and finally, the large classification is reserved for polyps 10 mm or greater. The most commonly encountered, over 80% - 90%, polyps sizes found during a routine colonoscopy include diminutive and small (von Karsa, Patnick, and Segnan 2012).

Complications that arise during removal of the polyps during polypectomy include bleeding, perforation, and post-polypectomy syndromes. Choo and Subhani also showed that bleeding is the most common difficulty that arises, followed by post-polypectomy syndromes, and
perforation. Bleeding is the most common because of the nature of removing the tissue inside of the colon by any means. Post-polypectomy syndromes include abdominal pain, fever, and inflammation. Lastly, perforation can lead to the most dangerous situations. This includes the removal and sometimes the shortening of the intestine, and life-threatening complications forming because of colon material entering the rest of the body.

*Electrosurgical Unit*

While removing the polyps, the use of one of two approaches is taken. Surgery with an electrosurgical unit (ESU) or surgery without. An ESU is an electrical device that produces a radiofrequency with an adjustable voltage and current, to either the forceps or snare instruments, to generate heat to aid in the removal of polyps or tissue while concurrently cauterizing the wound. The use of an ESU coins the term ‘Hot’ while using the snare or forceps, i.e. hot-snare. The Olympus PSD-30 (Olympus, Japan) was chosen for this experiment due to the ease of use, the ability to control the operation by modification of the foot pedal assembly (Robert 2013), along with the element of affordability.

There are three different types of modes that can be used with the ESU. They include a pure cutting mode, coagulation mode, and a blend of cutting and coagulation. These three modes of waveforms are generated by varying the duty cycle. A duty cycle of 100% produces the pure cut mode, a duty cycle of usually 10% or less is used to produce the coagulation mode, while somewhere in between is the blend mode. The pure cut mode has a risk of immediate post-polypectomy bleeding and the coagulation mode is more associated with delayed bleeding (Van Gossum et al. 1992). It has also been shown in live pig colons that regardless of the size of snare used, hot biopsy forceps produced deeper tissue damage (Chino et al. 2004), further verifying the use of hot-snare polypectomy as a preferred method.
As there are no standard guidelines as to which mode to use in a given situation, the discretion is completely up to the colonoscopist. In a study consisting of 189 physicians (Singh, Harrison, and Rex 2004), the three modes were compared by the regularity of use for each. This study concluded that coagulation was used by 46%, blend by 46%, and pure cut in only 3% of the practicing physicians. The remaining varied the current. Because of the popularity of the coagulation and blending modes, these two parameters are chosen for this experiment.

When applying either forceps or snare instruments, there are two ways to complete the circuit. These are either by use of monopolar or bipolar accessories. Monopolar instruments work by applying a current to the site of the polyp, usually through the end of the snare, and collecting this current on an electrode plate that is usually attached to the thigh of the patient. This means that the current has to pass through the body of the patient, which is not an ideal situation for taking measurements as this increases the error involved.

On the other hand, bipolar instruments use two active electrodes at the site of the polyp, meaning that there is no need for an externally placed electrode pad. In addition to a decrease in error in the measurements, bipolar instruments should be the ideal method, especially when using hot-forceps. This has been proven in a canine study (Savides et al. 1995), in which transmural injury occurred in 44% of the cases as compared to 5% for bipolar. Although the canine study does show a trend, note that the population size is small, only eight. Polypectomy with use of forceps is bipolar by design. The current flows from one side of the jaw to the other, completing the connection at the site of the probe.

*Electrosurgical Unit Instruments*

Many instruments are used during a colonoscopy while using the polypectomy technique. The choice of the instrument is determined based on the polyp size, shape, and location inside of the colon. They are classified according to the type of instrument used and whether they are ‘Hot’, with the aid of an ESU, or ‘Cold’, without the aid of an ESU.
Forceps have the advantage of having a high retrieval rate paired with a low complication rate. Forceps are recommended to use when the polyp size is less than 5 mm. Lee, Shim, and Jang reported that for diminutive lesions, the complete resection occurred at a rate of 92% for polyps 1-3 mm and 76% for polyps 4-5 mm (Lee, Shim, and Jang 2013). Forceps come in a variety of sizes and styles as well as being either ‘Hot’ or ‘Cold’. They range from, on average, 5-8 mm for the cup length and come with either jaw, spikes, or a central cup hole. It is also important to point out that even though forceps seem like the go-to method, the Korean guidelines for colorectal polypectomy do not recommend the hot-biopsy forceps as a standard method because it can make tissue diagnosis more difficult, as well as contribute to a risk of delayed bleeding or hypercoagulation syndrome (Lee et al. 2012).

Snare polypectomy is widely used for small colorectal polyps. This size of polyp also happens to be one of the most common types, as 90% of colorectal polyps are small or diminutive (Tsai and Strum 2011). Snare sizes and shapes come in a wide variety and have the added benefit of being able to swivel, or rotate, to obtain an optimal grip on the polyp. Generally, the diameter of the snare is used to classify the size. The most common shapes are round, oval, hexagonal, asymmetrical, and thick. Each of these different shapes also come in a variety of sizes to accompany. Barbed snares are not common, but are a great option when dealing with sessile or flat polyp shapes by allowing the snare to get a better grasp on the polyp. Because of the especially high number of polyps less than 9 mm in size, the mini oval (10-15 mm diameter) can be assumed to be the most commonly used snare as it is the recommendation for these size polyps (Park 2016). For this reason, the mini oval geometry will be used during experimentation.

A survey of 189 gastroenterologists concluded that the use of forceps was preferred for diminutive polyps while the use of an electrosurgical snare was the preferred method for removing small polyps (Singh, Harrison, and Rex 2004). The shift towards snare polypectomy for even diminutive polyps was reported, as the use of forceps is associated with incomplete removals of the polyp as well as higher complication rates (Anderloni et al. 2014). Others trying to standardize the
polypectomy technique also agree with using the snare for polyps less than 10 mm (Moss and Nalankilli 2017).

**Radiofrequency Ablation**

The radiofrequency ablation (RFA) technique works by applying an alternating current to the site of the tissue with the goal of generating heat to burst the cell membranes and in turn cutting while simultaneously cauterizing.

There are two thermal mechanisms that are dependent on the rate of electrical energy and temperature change of the tissue, they include resistive heating and frictional heating. Both of these mechanisms generate heat at the cellular level. Resistive heating occurs when the current is flowing through the cell, and the cell transforms the electrical energy, through resistance, into thermal. Partial charges from dipoles in the cells changing directions with the alternating current produces translational movement and ultimately frictional heating (Zinder 2000).

By controlling the current density as a function of time and voltage, different therapeutic effects are accomplished during the electrosurgery. Current density is a measure of current concentration or intensity. The variables that affect the current density include some of which can be controlled by the user and some which are based on the patient. The variables that can be controlled by the user include the length of time the current is applied to the site, the waveform, and the power applied. The thermal heating effect on the cells of the tissue has a directly proportional relationship to the current density. One way to adjust the current density is to alter the duty cycle. A low duty cycle can generate a wide and shallow thermal area, and a high duty cycle can generate a narrow and deep incision (Morris and Bowers 2016). The variables which are out of control of the user and which vary from patient to patient include the total impedance, from the size of the polyp to the size of the patient.
Bioelectrical Impedance

Tissue displays the properties of both conductors and dielectrics, meaning that the tissue contains both conducting and dielectric terms. The complexity that arises from the body includes both resistance and capacitive resistance known as reactance. Together the combination of both resistance and reactance is known as impedance. The resistance arises from both the extracellular water (ECW) and intracellular water (ICW) while the capacitance arises from the cell membranes (Kyle 2004). The cell membrane is composed of mainly proteins and lipids and determines how the current flows inside of the cell. Being that the cell membrane is highly resistive (Pethig 1984), it is expected that the impedance will drop with increasing frequency. This is, in fact, the case (Bertemes-Filho 2002). Another factor in the tissue impedance is that the tissue is not completely homogeneous or isotropic, it is anisotropic; meaning that the conductivity term is different if taken in different directions. To complicate the situation further, additional variables such as temperature, electrode and tissue interface impedance, and even the type of electrode are all relevant factors. Because of these complex situations inside of the cell, numerical modeling can be difficult. Even in the ideal of cases, simplifications and assumptions need to be made which can cause large errors.

There is a relationship in the change of impedance in the tissue and the damage done at the ablation site (Morris and Bowers 2016). As the thermal damage increases at the ablation site, so too does the impedance. The ablation site is where perforations and bleeding can cause severe post-surgery complications and even death.

This study focuses on monitoring the change in impedance during the operation of the ESU, which is not a new idea. Multiple big manufactures of ESU’s have this integrated into their devices. It is more commonly seen however for the bipolar method, which both sending and receiving electrodes of the current flow through the accessory. The difference in this study is the fact that this is done using a hot snare, which uses the monopolar method. This brings on additional complications in the accuracy of the measurements due to the length of the wire of the snare and grounding patch easily being over two meters and having to integrate the patients’ body, not just the polyp, into the
measurements. In this case, the circuit would be the path the current takes from the ESU through the snare, then through the polyp and patient, and back to the ESU through the ground patch.

**Bioelectrical Impedance Methods**

There are two common methods used for bioelectrical impedance analysis (BIA). They include the single frequency method and the multi-frequency method. The single frequency method uses measurements taken at a single frequency of 50kHz to determine the impedance. This frequency is chosen due to the weighted sum of the ECW and ICW resistivities (Kyle 2004). Although this method cannot determine differences in the ICW.

The second method used for BIA is the multi-frequency method. This method includes taking multiple impedance measurements over a range of frequencies usually between 5kHz and 200kHz. At frequencies below 5kHz and above 200kHz, poor reproducibility has been noted especially at the lower frequencies (Hannan et al. 1994). At zero, or low, frequency the cell membrane acts like an insulator and the applied current does not pass through the cell. This gives a good representation of the resistance of the ECW and is referred to as \( R_0 \). At infinite, or high, frequency the cell membrane acts as a near perfect capacitor and gives a good representation of both the ECW and the ICW and is referred to as \( R_\infty \). Since practicality prevents the use of DC current or infinite frequency measurements to be performed, the use of a Cole-Cole plot to predict the values for \( R_0 \) and \( R_\infty \) is used (Cole and Cole 1941). This curve is formed by plotting the negative reactance, \(-X_C\), vs resistance, \( R \). An example of this plot is shown in Figure 1.1.
To model the inside of the human colon, there are three possibilities. These include the resistor-resistor-capacitor (RRC) electric circuit, gel block, and actual tissue samples from living organisms. The RRC circuit is the equivalent electrical circuit, Figure 1.2, used to mimic the human body (Kyle 2004). Where the resistance of the ICW is denoted by $R_I$, the resistance of the ECW is denoted by $R_E$, and the cell membrane is denoted by $C_M$. The gel block is interesting in the fact that the mechanical properties, as well as the electrical properties, can all be fine-tuned. The mechanical properties that can be tuned include size, shape, and stiffness. The electrical properties that can be tuned are the impedance. The gel block test model is made from polyacrylamide gel (PAG) that is commonly used in biological sciences. As for the alternative, the tissue samples can be sourced from an animal such as a goat or pig. For this study, the use of the RRC equivalent circuit and tissue samples of the porcine colon are used.
Figure 1.2. RRC equivalent circuit to mimic the human body

Current Pump

To provide accurate and consistent measurements, the current pump needs to provide a stable current output over a range of frequencies and loads. A common approach used for current sources is the voltage controlled current sources (VCCS) often with the Howland current pump design. The Howland current pump uses an operational amplifier for both the positive and negative feedbacks. Because the output impedance is influenced by how well the resistors are matched, the tolerance of the components used are a major consideration. The output impedance can be decreased by parasitic capacitances especially at the higher frequencies. A current pump used for BIA should be able to provide stable current for frequencies ranging from 1kHz to 1MHz for load ranges of 25Ω to 10kΩ (Bouchaala et al. 2012). Bouchaala et al. found that the Howland current pump had an error of 0.98% at low frequencies and 3.99% at 1MHz for a load of 10.2kΩ. Another study examined four different operational amplifiers including the models OPA655, TL081, OP07, and uA741 for a range of 1Hz to 100MHz (Bertemes-Filho et al. 2012). The authors found that the OPA655 operational amplifier showed a stable current up to 1MHz before varying while the other three varied the current between 100kHz and 1MHz. The output impedance began to dropped off at 100kHz for the OPA655 while the other three operational amplifiers began to drop off at 1kHz. For these reasons, the OPA655 operational amplifier was used for the current pump in this study.
Objectives

There are three main objectives of this study. The first of which deals with the design and construction of the feedback system. Many different pieces of equipment and components need to be used and constructed together to perform the task of measuring the impedance while operating the ESU. The second objective follows the first with the testing and tweaking of the operation of the feedback system. This objective deals with troubleshooting the building of the circuits as well as smoothing out the fine details involved with the programming of the feedback system. The third and final main objective deals with the testing and verification of the system. The feedback system must prove able to automatically stop given a certain impedance threshold and then be applied to the porcine colon to minimize tissue damage.
CHAPTER 2
METHODS

*Devices*

The Olympus PSD-30 (Olympus, Japan) ESU was used as the source of the high-frequency alternating current used in this study. The PSD-30 has three different cut modes as well as three different coagulation modes. The fundamental frequency is 350kHz with the ability to change the power settings from 2W-50W in 5W increments. It also has an open-circuit output voltage of almost 900V (Olympus 2001).

To power the feedback system, a CUI Inc PYB10-Q24-D5 DC-DC converter (CUI INC, USA), which supplies a ±5Vdc output was used. The DC converter takes an input voltage range from 9-36V and can supply an output current from ±50mA to ±1000mA with a maximum ripple and noise of 80mVpp (CUI 2013). Supplying the input voltage to the DC converter is a Keysight E3633A benchtop DC power supply (Keysight Technologies, USA), capable of supplying a DC voltage output up to 20V and 10A (Keysight 2017).

The 1Vpp sine wave used for the reference signal was supplied with a B&K Precision model 4053 Function/Arbitrary Waveform Generator (B&K Precision Corp, USA). This device can provide sinusoidal waves with frequencies ranging from 1μHz to 10MHz, has an accuracy of ±100ppm, with a resolution of 1μHz. It is capable of outputting from 2mVpp up to 5Vpp for frequencies up to 10MHz, has a 4-digit amplitude resolution, and an amplitude accuracy of ±0.3dB + 1mVpp of setting value at 100kHz (BK Precision 2014).

Voltage amplitude and phase difference were measured with the Keysight InfiniiVision DSOX2022A Digital Oscilloscope (Keysight Technologies, USA). This oscilloscope has 2 channels, a bandwidth of 200MHz, a maximum sampling rate of 1 GS/s/channel, and an input sensitivity of 1mV/div (Keysight 2018).
The analog to digital converter (ADC) used to acquire the voltage across both the DUT and reference resistor was a National Instruments USB NI 6353 data acquisition (DAQ) device (National Instruments Corp, USA). This device has 32 analog input channels and 48 digital input/output channels with a maximum sample rate of 1.25 MS/s. It also has an ADC resolution of 16 bits with a 10ns timing resolution (National Instruments 2016).

The Arduino UNO (Arduino LLC, Italy) microcontroller was used to coordinate the timing for the feedback system. This microcontroller has 14 digital input/output pins and 6 analog input pins. It has a maximum DC current of 20mA per pin and runs with a clock speed of 16Mhz (Arduino 2019).

The Impedimed SFB7 (Impedimed Ltd, Australia) was used to take impedance measurements of the porcine colon. This is a BIS device designed for measuring whole-body impedance. It measures 256 frequencies from 4kHz to 1MHz with an accuracy of ±1.0% for the impedance range of 50Ω to 1100Ω. It has a phase resolution of 0.1° (Impedimed 2005).

**Electrical Components**

Due to the inability of the Arduino UNO microcontroller to source enough current to switch the relays used in the feedback system effectively, a 2N3904 NPN bipolar transistor configured as a switch was used. This allowed the microcontroller to still control the timing, while the source of the current supplied was from the DC converter.

The first relays used were the CPC1988 high-power solid-state relays (IXYS Integrated Circuits Division, USA). These solid-state relays are capable of blocking 1000Vp with a maximum turn-on switching speed of 20ms and a maximum turn-off switching speed of 5ms (IXYS 2018). The CPC1988 relays were used to block the voltage from the ESU.

The second relays used include the 9002 SIP reed relays (COTO Technology, USA). These reed relays are capable of switching a maximum of 200V with an operating time of 0.35ms and a
release time of 0.1ms (COTO 2019). The 9002 SIP reed relays were used to operate the firing of the ESU.

*Modified Electrosurgical Unit*

The modification of the PSD-30 ESU was accomplished by way of the foot pedal assembly, Figure 2.1. This allows for the reading of when the user presses down on the assembly to initiate the firing, as well as a place to stop the ESU from firing by interrupting the signal sent to it. The foot pedal assembly works by use of two normally open momentary switches. One switch is used to control the cutting mode, while the other switch is used to control the coagulation mode. The modification was accomplished by way of these two switches. The wires connecting from the switches were cut, and then the microcontroller was placed in between each wire. This gave the microcontroller two inputs and two outputs. When one of the pedals are pressed, a 5V signal is passed, on the other hand, when the pedals are depressed, the signal reads 0V. This allows for the microcontroller to determine the state of the switch as either digitally high, the user is pressing the button to fire, or digitally low, the user is not pressing the button. With this information, the microcontroller can tell the ESU to fire or not. Essentially the user presses the button on the foot pedal assembly telling the microcontroller they wish to fire the system, and then the microcontroller tells the ESU whether to fire or not, effectively playing the middle man.
Measuring System

The second portion of the feedback system comprises of the measuring system. This part of the feedback system is used to take the impedance measurement of the device under test (DUT), which in this case is the model the alternating current passes through. The measuring system consists of multiple parts which each play a vital role in the operation. The first of which is the DC power supply. This power supply is used as the input voltage to the DC-DC converter that supplies ±5V to the Howland current pump, operational amplifiers, and relays. In addition, a function generator is used to produce the 50kHz 1Vpp sinusoidal wave that is used as the reference signal. The single 50kHz frequency was chosen for two reasons. The first of which has to deal with timing. Although multifrequency bioimpedance spectroscopy is the preferred method, as it allows for a complete picture of the properties of the subject (Kyle 2004), this method takes too long to be practical in this application. To perform a reasonable multifrequency measurement, frequencies from about 5kHz to
500kHz need to be measured, which dismisses this technique. Knowing that a single frequency measurement will be required, leads to the second reason. The 50kHz frequency is the most commonly used frequency when performing a single frequency bioelectrical impedance measurement. This was discussed earlier and is due to the weighted sum of ECW and ICW resistivities at this frequency (Kyle 2004). With knowing that the current source supplies a constant current of 200µApp RMS at this reference frequency, the impedance of the DUT and reference resistor can be calculated. To calculate these impedance values, two voltage output signals are collected with a DAQ device as shown in Figure 2.2 where the reference resistance is 475Ω. Before the signals make it to the DAQ however, they are passed through a buffer, also known as an active electrode (AE), and then through an instrumentation amplifier with a gain of two. The buffer is used to stabilize the signal, while the amplifier is used to increase the small output voltage being sent into the DAQ for higher resolution. These voltages collected by the DAQ are then read into LabVIEW (National Instruments, USA) via the computer. The sampling frequency of the DAQ is set to 251kHz. This adheres to the Nyquist rate and ensures the samples are not a constant multiple of the measuring frequency confirming that the full waveform is measured. The number of samples to read at a time was set to 2000, which in turn relates to a measurement of every 8ms. This allows a sufficient number of waveforms to be measured to make the impedance calculations, as well as be fast enough to be practical when being used in a real-life situation. The 475Ω reference resistor is used to confirm that the voltage measurements taken of the DUT are accurate. To ensure this, the measured voltage drop should be an ideal 268.7mV, which relates to a resistance of 475Ω. This value is derived from multiplying the current from the pump of 282.84µA with the known reference resistance of 475Ω, and then multiplying by a factor of two for the amplifier. With this measurement, the system can be said to accurately measure the voltage drop across the DUT.
Control System

Now that the modification of the ESU and measuring system is completed, the control system part of the feedback system needs to be developed. For the control system, the Arduino UNO microcontroller is used to coordinate the firing, measuring, and the on and off synchronization of the relays. The microcontroller utilizes three inputs and five outputs to achieve this. Two inputs are used for reading the state of the foot pedal assembly, one for coagulation and one for cut mode, while the third input is connected to the DAQ which is attached to an interrupt pin on the microcontroller. This third input is used by LabVIEW to stop the ESU before perforation occurs. The five outputs include one for each of the two sets of two CPC1988 solid state power relays. These high-power solid-state relays are used to separate the DUT between the measuring system and the modified ESU. They were chosen because of the high $1000V_p$ blocking voltage which is required to block the maximum output voltage of about 900V that the PSD-30 ESU is capable of. Two more outputs are used to control each of the 9002 SIP reed relays which are used to send a 5V signal to the ESU to fire either the coagulation
or cut mode. As the signal required to fire the ESU is low voltage, the only concern was that of speed. That is why the 9002 SIP reed relay was chosen, it has an operating time of 0.35ms and a release time of 0.1ms. It is important to note that each of these four outputs is controlling the relays through NPN bipolar transistors configured to perform as a switch. This was done to allow the relays to be powered by the DC-DC converter’s 1000mA power supply, as the microcontroller is not able to source enough current for proper switching. The final output is connected to the DAQ and tells LabVIEW whether it is an acceptable time to measure or not. This output is especially important as the feedback system should not take measurements while the ESU is firing.

Some considerations that had to be made when configuring the control system includes adding a delay of 25ms between the transition of turning on and off the relays that separate the current source, DUT, and ESU. This was done to ensure that no high voltage was sent back into the current source. Another consideration had to be made in terms of a 25ms delay between turning on a relay and sending the signal to the DAQ to start measuring. This fixed an error where the resistance would be measured to be extremely high as the initial measurements were made while the circuit was still slightly open, during the switching of the relay. This forced LabVIEW to tell the microcontroller that the resistance value had been surpassed and to stop prematurely. The last consideration that had to made concerns the ESU. The smallest amount of time that the ESU needed to fire before being turned off was found to be 75ms. If the time was any less than this then the ESU would display an error ‘Er P’ on the front panel. This error is caused by the ESU thinking that the P cord of the device is broken. To complete one full cycle of measuring the DUT to firing the ESU and back to measuring takes 184ms. This means that the ESU fires 5.4 times a second for a total on time of 405ms, effectively having a duty cycle of about 41%. The Arduino sketch can be found in Appendix A. Figure 2.3 displays the complete impedance-controlled feedback system; a) modified foot pedal, b) measuring system, c) control system.
Now that the feedback system is complete, the operation of the system is as follows. As the user presses the foot pedal, a 5V signal is sent to the microcontroller indicating either the coagulation or cut switch has been pressed. The microcontroller reads this input and starts by opening the solid-state power relays that connect the measuring system to the DUT, which will be referred to as the ‘measure relays’. While this is happening, the solid-state power relays connecting the ESU to the DUT are closed, these relays will be referred to as the ‘ESU relays’. This separates the measuring system from the DUT while the ESU is firing, and closes the connection between the DUT and ESU while the 350kHz alternating current is being applied. While the foot pedal is still being pressed, the microcontroller opens the ESU relays and closes the measuring relays. This now allows for safe and accurate measurements. When this switch happens, the microcontroller sends a signal to the DAQ to tell LabVIEW to measure the voltage drop across the reference resistor and the DUT. LabVIEW takes these voltage measurements and converts them into a resistance, using the known current of

Figure 2.3. Complete impedance-controlled feedback system; a) modified foot pedal assembly, b) measuring system, c) control system

Operation
the system, and decides whether or not there has been too much thermal damage. From here, the microcontroller tells LabVIEW to stop measuring, and the ESU and measure relays switch orientation again. The ESU continues to send an alternating current to the DUT, and the process is repeated over and over again until the calculated resistance reaches some threshold value. Once this threshold is reached, LabVIEW sends a signal to the microcontroller to interrupt this process and turn off the ESU firing process. This ultimately stops the DUT from receiving any more alternating current from the ESU. A schematic of the feedback system is shown in Figure 2.4. The RRC block in the schematic diagram is made of two resistors and a capacitor in parallel. This is explained in more detail in the following section.

![Schematic diagram of the feedback system](image)

**Figure 2.4. Schematic diagram of the feedback system**
To represent the biological system of the patient, the DUT consists of an RRC circuit to mimic the features of the body. The values of the resistors and the capacitor for the verification stage of the feedback system were chosen such that they replicated the Cole-Cole curve of a patient. These values were found by first measuring the Cole-Cole curve using the ImpediMed SFB7 bioimpedance spectroscopy device. As in vivo testing is not allowed in this stage of the study, ex vivo test need to be performed. Taking this into account, the device was connected at the same location that the ground patch would be on the thigh. The other end was first connected to the front of the torso, about were the colon would be, and then on the back side of the torso. The average values for the front of the torso to the thigh were measured to be 62.06Ω for \( R_0 \) and 25.35Ω for \( R_\infty \). While the average values for the back of the torso to the thigh were measured to be 65.50Ω for \( R_0 \) and 25.28Ω for \( R_\infty \). The \( R_0 \) and \( R_\infty \) values of these two positions were then averaged to give a close representation of what the Cole-Cole curve would look like if the snare were inside of the colon. The average values of these were calculated to be 63.78Ω for \( R_0 \) and 25.32Ω for \( R_\infty \). With these design specifications, the RRC circuit was created with a 64Ω resistor for \( R_E \), a 18Ω resistor for \( R_I \), and a 1nF capacitor for \( C_M \). In series with the RRC circuit was a potentiometer that was used to simulate the change in impedance that occurs to the biological tissue during the applied current from the ESU.

The RRC circuit had to be redesigned for the testing of the porcine colon samples as the RRC circuit used for the verification step was too small with a narrow range of only 56Ω between \( R_0 \) and \( R_\infty \). This was found to not be ideal as the noise in the system with the colon sample did not allow for a clear Cole-Cole curve to be measured due to the impedance of the sample being greater than that of the RRC circuit. The values chosen for this equivalent circuit were those used in the test cell for the SFB7 device and model the full body. They include a \( R_I \) of 1.21kΩ, \( R_E \) of 619Ω, and \( C_M \) of 1nF. This calculates to an \( R_0 \) value of 619Ω at zero frequency and an \( R_\infty \) value of 409.5Ω at infinite frequency. This increased the range between \( R_0 \) and \( R_\infty \) to 209.5Ω and allowed for a clearer Cole-Cole curve.
Colon Sample Preparation

To prepare the porcine colon, it was first washed and rinsed with water. After the organic material was removed from the colon by the water, it was submerged in ethyl alcohol and stored in a freezer for preservation until the time came to perform tests. When a test was ready to be performed on the colon, it was first removed from the alcohol and cut into 1in x 1in (2.54cm x 2.54cm) square samples. This sample was then placed in line with the feedback system by way of a 3M Red Dot electrode (3M, USA) connected to the ground patch, and the snare pressed on top of the porcine colon sample, Figure 2.5. The Red Dot electrode was chosen due to the ease of connecting the ground patch wire coming from the ESU to it, as well as replicating the gel grounding pad that is normally attached to the thigh of the patient during monopolar electrosurgery.

Figure 2.5. Porcine colon sample setup with snare
CHAPTER 3

RESULTS

Current Pump

To test that the current pump supplies a consistent current across the frequencies used in this study, the voltage drop was measured across a 475Ω resistor and displayed in Figure 3.1.

![Figure 3.1. Current pump test with the voltage drop across a 475Ω resistor](image)

The frequency range used to test the current pump was from 3kHz to 1MHz. An overall upwards trend can be seen from the graph. The minimum voltage drop was found at 3kHz with a measurement of 133.9mV while the maximum voltage drop occurred at 300kHz with a measurement of 146.1mV. This calculates to a spread of 12.2mV. At the 50kHz frequency, the voltage drop was measured to be 139.8mV which is 4% higher than the ideal 134.4mV. The current pump was found to produce an acceptable current throughout the range of frequencies used in this study.
**x2 Multipliers**

The operational amplifiers, configured for a gain of two, used to increase the small voltage signal from the DUT and reference resistor and sent into the DAQ need to be tested. Figure 3.2 displays the results for the first amplifier while Figure 3.3 displays the results for the second multiplier.

![Graph](image)

**Figure 3.2. First amplifier with an ideal gain of two**

The first amplifier had a minimum gain of 1.98 found at 15kHz with a maximum gain of 2.15 at 1MHz. For the 50kHz frequency used in this study, the gain was found to be the ideal 2.00. This was found to be within an acceptable range.
The second amplifier had a minimum gain of 1.99 also found at 15kHz with a maximum gain of 2.14 at 1MHz. For the 50kHz frequency used in this study, the gain was found to 2.02. This calculates to a 1% difference from the ideal gain of 2.00 and was also found to be within an acceptable range.

**Verification of Feedback System**

As the measurements are all taken at the 50kHz frequency and the equivalent circuit does not change values with the applied alternating current, a potentiometer was placed in series with the RRC circuit. This allows for the change in impedance of the DUT, by way of turning the potentiometer, to simulate the increase that would be observed if a tissue sample were being measured as an alternating current was being passed through it.

Multiple tests of the system were performed on the DUT with threshold values set to 500Ω, 750Ω, and 1000Ω. These values were chosen to represent the range of the DUT circuit, which was
around 1200Ω. These tests were performed with the soft coagulation mode at the 2W power settings on the ESU. The 2W power setting is the lowest power setting on the PSD-30 ESU and was chosen due to the limitations of the power capabilities of the resistors and capacitors used in the DUT. Although the lowest power setting was used in this experiment, this still confirms proof of concept.

The output voltage from the ESU was not measured by the DAQ as the high voltage was beyond the limitations of the device. The output voltage from the ESU was measured directly by the oscilloscope during the firing operation for different values of impedance. The beginning resistance in each trial was measured to be 68Ω as this was the value with the added potentiometer at the lowest position. There were 19 total ESU output voltage measurements made. One voltage measurement was made at the 68Ω starting resistance, while the other 18 were measured for different values of resistance ranging from 100Ω to 1000Ω in 50Ω increments. This information was then overlaid with the data for the impedance measurements. The results of each trial are displayed in Figures 3.4-6.

Figure 3.4. 500Ω cut-off threshold verification test
Figure 3.5. 750Ω cut-off threshold verification test

Figure 3.6. 1000Ω cut-off threshold verification test
In each of the trial runs, the power was cut off from the ESU at each of the specified threshold values as expected. The time between data points was also observed to be the correct time delay of 184ms that was implemented in the programming. While these tests were being performed, the voltage from the reference resistor was being monitored. This reference resistance stayed within ±5Ω of the known resistance of 475Ω.

For the 500Ω threshold trial, the impedance started at 68Ω and the potentiometer was adjusted until the impedance measurement read 500Ω in which the voltage output from the ESU was stopped due to reaching the threshold value. The voltage was measured at 40V from the beginning and started to rise once the impedance started to increase. The final measured value, before the interruption of the voltage output, was measured to reach 85V. A similar trend can be observed for both of the 750Ω and 1000Ω threshold trials. While the starting voltage was the same for each of the three trails, the final voltage measured was different as the final impedance value increased. For the 750Ω threshold trial, the final voltage was measured to be 94V while the 1000Ω threshold trial reached a maximum voltage of 99V.

While the slope of the line for the DUT impedance values was determined by how fast the potentiometer was increased, the line follows that of a first order system. The slope for the 500Ω trial was 133 with an R-squared value of 0.981, the 750Ω trial had a slope of 145 with an R-squared value of 0.981, and the 1000Ω trial had a slope of 167 with an R-squared value of 0.998. On the other hand, the output voltage from the ESU was determined to be a second order system, with an R-squared value of 0.989, as the voltage did not increase proportionally to the impedance. Although the order number does not matter, as it could be any order, the important fact is the system response at the threshold.
Perforation Measurements

The feedback system now needs to be programmed to determine at what point perforation ensues and stop the alternating current from the ESU before this occurs. As the size of the patient and the polyp vary, a finite impedance threshold to stop the ESU, as used in the verification step, needs to be abandoned in favor of a more dynamic approach. This new method will be based on the percent change in impedance. This approach is more appropriate as the initial conditions vary in each situation.

To collect both the prefire and postfire data that was needed to assess how much the impedance of the porcine colon sample has changed, due to the thermal damage, manually measuring with an oscilloscope was not feasible. During the initial trials, the time required to take multiple accurate measurements with an oscilloscope was found to take too long. As the sample sat on the gel pad in the open, the water in the sample started to evaporate and dry out the sample. This caused a noticeable change in impedance over a short period of time and skewed the data. This is where the use of the ImpediMed SFB7 comes into play. The SFB7 is capable of taking 256 measurements ranging from 4kHz to 1MHz in the time span of just about one second. The SFB7 was used to take three measurements before and three measurements after the applied current. MATLAB R2017a (MathWorks, USA) and Excel 2016 (Microsoft Corp, USA) were used to analyze the data. The circle fit used was the Pratt method (Chernov 2009, Pratt 1987). Appendix B shows the MATLAB script used for the data analysis.

To determine what the critical percent change in impedance value should be, tests need to be performed to first determine the minimum time required for perforation to occur. This was done at the highest power setting of 50W to determine the maximum range for the rest of the trials.

Visual inspection of the porcine colon sample was performed to determine at what point perforation has occurred, as the ESU was fired multiple times for different durations. In Figure 3.7, the Cole-Cole curves were plotted, along with the tissue samples, for a firing duration of 2s (a), 3s (b), and 4s (c) at the 50W setting.
Figure 3.7. 50W perforation test; a) 2s, b) 3s, c) 4s

For the 2s test, the Cole-Cole curve still supported the characteristics of having both ICW and ECW as the measurements still follow the fitted curve with clear changes in reactance. Although after two seconds it is evident that at the low frequencies, the curve has started to level out. This indicates a loss in ECW. The fitted curve shows an \( R_0 \) of about 1060Ω with an \( R_\infty \) value of just under 600Ω. Visual inspection exposed no signs of perforation. For the 3s test, the ECW is shown to further level out while the ICW starts to also show signs of this as well. This trend is expected, as the more thermal energy introduced burst more cell membranes deeper in the tissue. After three seconds, the fitted curve shows \( R_0 \) close to 2000Ω while \( R_\infty \) approaches 0Ω. Visual inspection of this sample also showed no signs of perforation. Moving on to the 4s test, the Cole-Cole curve displayed clear signs of damage. Both the ECW and ICW have leveled out. This shows that at all frequencies measured, the reactance did not change much. This means that there is little water left in the sample and that the majority of cell membranes have burst. There is no \( R_0 \) or \( R_\infty \) value to report as the fitted line did not cross the x-axis. Visual inspection showed that indeed perforation had occurred. Based on these graphs and visual inspections, perforation was deemed to occur around the 50W power setting for a firing duration of 3s. Therefore, this limit was chosen as the maximum parameters to test.
Prefire vs Postfire Impedance

Now that the point of perforation has been discovered, further test using multiple power settings and firing durations was conducted to observe how the impedance changed. The power settings used ranged from 10W-50W over firing times of 1s-3s. This range was chosen based on the maximum power and duration found previously to be the cap. Each of the trials is shown in Figures 3.8-22 to demonstrate how the Cole-Cole curve changes from prefire to postfire. The left curve is the prefire measurement while the right curve is the postfire. The average of three measurements is plotted with the error bars representing the minimum and maximum values. Because the amount of force the snare applied to the tissue sample also contributes to the thermal damage, a scale was used to measure the force applied and was adjusted to be the same for all tests. Before every trial, the snare was situated on the sample in such a way that the force applied for all tests ranged from 0.04-0.05N. Although 256 data points for each trial are collected, only 132 of these points are used in the calculations to determine the $R_0$ and $R_\infty$ values. These 132 data points used correlate to the measurements ranging from 25kHz to 500kHz. It is common to use this smaller range as it has been proven that measurements below and above this frequency range are normally not representative of the real picture (Kyle 2004). Of these 132 data points, only 14 equally spaced points are plotted on the graph to allow for a clear understanding of what the graphs represent. Otherwise, the graph is too cluttered and does not allow for good visual analysis.
For the power setting of 10W with a firing duration of 1s, the prefire Cole-Cole curve had a SEE of 0.60Ω and revealed an $R_0$ of 1013Ω, an $R_\infty$ of 766Ω, with a 50kHz measurement of 942Ω. The postfire Cole-Cole curve had a SEE of 0.63Ω and revealed an $R_0$ of 1060Ω, an $R_\infty$ of 808Ω, with a 50kHz measurement of 986Ω. This calculates to an increase in impedance of 4.64% for $R_0$, 5.48% for $R_\infty$, and 4.67% at 50kHz.

For the power setting of 10W with a firing duration of 2s, the prefire Cole-Cole curve had a SEE of 2.08Ω and revealed an $R_0$ of 1517Ω, an $R_\infty$ of 1214Ω, with a 50kHz measurement of 1422Ω.
The postfire Cole-Cole curve had a SEE of 2.38Ω and revealed an $R_0$ of 1613Ω, an $R_\infty$ of 1305Ω, with a 50kHz measurement of 1517Ω. This calculates to an increase in impedance of 6.33% for $R_0$, 7.50% for $R_\infty$, and 6.68% at 50kHz.

![Figure 3.10. 10W 3s prefire vs postfire Cole-Cole plot](image)

For the power setting of 10W with a firing duration of 3s, the prefire Cole-Cole curve had a SEE of 0.83Ω and revealed an $R_0$ of 1146Ω, an $R_\infty$ of 884Ω, with a 50kHz measurement of 1070Ω. The postfire Cole-Cole curve had a SEE of 1.31Ω and revealed an $R_0$ of 1254Ω, an $R_\infty$ of 987Ω, with a 50kHz measurement of 1178Ω. This calculates to an increase in impedance of 9.42% for $R_0$, 11.65% for $R_\infty$, and 10.09% at 50kHz.
For the power setting of 20W with a firing duration of 1s, the prefire Cole-Cole curve had a SEE of 1.42Ω and revealed an $R_0$ of 1139Ω, an $R_\infty$ of 791Ω, with a 50kHz measurement of 1015Ω. The postfire Cole-Cole curve had a SEE of 1.44Ω and revealed an $R_0$ of 1161Ω, an $R_\infty$ of 805Ω, with a 50kHz measurement of 1034Ω. This calculates to an increase in impedance of 1.93% for $R_0$, 1.77% for $R_\infty$, and 1.87% at 50kHz.

For the power setting of 20W with a firing duration of 2s, the prefire Cole-Cole curve had a SEE of 0.44Ω and revealed an $R_0$ of 937Ω, an $R_\infty$ of 689Ω, with a 50kHz measurement of 866Ω.
The postfire Cole-Cole curve had a SEE of 0.71Ω and revealed an $R_0$ of 1017Ω, an $R_\infty$ of 763Ω, with a 50kHz measurement of 941Ω. This calculates to an increase in impedance of 8.54% for $R_0$, 10.74% for $R_\infty$, and 8.66% at 50kHz.

Figure 3.13. 20W 3s prefire vs postfire Cole-Cole plot

For the power setting of 20W with a firing duration of 3s, the prefire Cole-Cole curve had a SEE of 0.77Ω and revealed an $R_0$ of 1127Ω, an $R_\infty$ of 829Ω, with a 50kHz measurement of 1028Ω. The postfire Cole-Cole curve had a SEE of 1.58Ω and revealed an $R_0$ of 1324Ω, an $R_\infty$ of 972Ω, with a 50kHz measurement of 1202Ω. This calculates to an increase in impedance of 17.48% for $R_0$, 17.25% for $R_\infty$, and 16.93% at 50kHz.

Figure 3.14. 30W 1s prefire vs postfire Cole-Cole plot
For the power setting of 30W with a firing duration of 1s, the prefire Cole-Cole curve had a SEE of 0.61Ω and revealed an $R_0$ of 869Ω, an $R_\infty$ of 623Ω, with a 50kHz measurement of 796Ω. The postfire Cole-Cole curve had a SEE of 0.45Ω and revealed an $R_0$ of 905Ω, an $R_\infty$ of 663Ω, with a 50kHz measurement of 835Ω. This calculates to an increase in impedance of 4.14% for $R_0$, 6.42% for $R_\infty$, and 4.90% at 50kHz.

![Figure 3.15. 30W 2s prefire vs postfire Cole-Cole plot](image)

For the power setting of 30W with a firing duration of 2s, the prefire Cole-Cole curve had a SEE of 0.38Ω and revealed an $R_0$ of 934Ω, an $R_\infty$ of 683Ω, with a 50kHz measurement of 862Ω. The postfire Cole-Cole curve had a SEE of 0.62Ω and revealed an $R_0$ of 1066Ω, an $R_\infty$ of 765Ω, with a 50kHz measurement of 969Ω. This calculates to an increase in impedance of 14.13% for $R_0$, 12.01% for $R_\infty$, and 12.41% at 50kHz.
For the power setting of 30W with a firing duration of 3s, the prefire Cole-Cole curve had a SEE of 0.62Ω and revealed an \( R_0 \) of 988Ω, an \( R_\infty \) of 717Ω, with a 50kHz measurement of 902Ω. The postfire Cole-Cole curve had a SEE of 0.99Ω and revealed an \( R_0 \) of 1221Ω, an \( R_\infty \) of 855Ω, with a 50kHz measurement of 1092Ω. This calculates to an increase in impedance of 23.58% for \( R_0 \), 19.25% for \( R_\infty \), and 21.06% at 50kHz.

For the power setting of 40W with a firing duration of 1s, the prefire Cole-Cole curve had a SEE of 2.43Ω and revealed an \( R_0 \) of 1228Ω, an \( R_\infty \) of 816Ω, with a 50kHz measurement of 1080Ω. The postfire Cole-Cole curve had a SEE of 1.88Ω and revealed an \( R_0 \) of 1267Ω, an \( R_\infty \) of 910Ω, with
a 50kHz measurement of 1144Ω. This calculates to an increase in impedance of 3.18% for $R_0$, 11.52% for $R_\infty$, and 5.93% at 50kHz.

Figure 3.18. 40W 2s prefire vs postfire Cole-Cole plot

For the power setting of 40W with a firing duration of 2s, the prefire Cole-Cole curve had a SEE of 1.11Ω and revealed an $R_0$ of 895Ω, an $R_\infty$ of 569Ω, with a 50kHz measurement of 784Ω. The postfire Cole-Cole curve had a SEE of 1.66Ω and revealed an $R_0$ of 1102Ω, an $R_\infty$ of 629Ω, with a 50kHz measurement of 894Ω. This calculates to an increase in impedance of 23.13% for $R_0$, 10.54% for $R_\infty$, and 14.03% at 50kHz.

Figure 3.19. 40W 3s prefire vs postfire Cole-Cole plot
For the power setting of 40W with a firing duration of 3s, the prefire Cole-Cole curve had a SEE of 0.73Ω and revealed an $R_0$ of 833Ω, an $R_\infty$ of 543Ω, with a 50kHz measurement of 737Ω. The postfire Cole-Cole curve had a SEE of 1.94Ω and revealed an $R_0$ of 1174Ω, an $R_\infty$ of 637Ω, with a 50kHz measurement of 917Ω. This calculates to an increase in impedance of 40.94% for $R_0$, 17.31% for $R_\infty$, and 24.42% at 50kHz.

![Figure 3.20. 50W 1s prefire vs postfire Cole-Cole plot](image)

For the power setting of 50W with a firing duration of 1s, the prefire Cole-Cole curve had a SEE of 1.64Ω and revealed an $R_0$ of 1331Ω, an $R_\infty$ of 949Ω, with a 50kHz measurement of 1195Ω. The postfire Cole-Cole curve had a SEE of 1.53Ω and revealed an $R_0$ of 1403Ω, an $R_\infty$ of 1055Ω, with a 50kHz measurement of 1283Ω. This calculates to an increase in impedance of 5.41% for $R_0$, 11.17% for $R_\infty$, and 7.36% at 50kHz.
For the power setting of 50W with a firing duration of 2s, the prefire Cole-Cole curve had a SEE of 1.33Ω and revealed an \( R_0 \) of 1328Ω, an \( R_\infty \) of 849Ω, with a 50kHz measurement of 1144Ω. The postfire Cole-Cole curve had a SEE of 2.74Ω and revealed an \( R_0 \) of 1328Ω, an \( R_\infty \) of 849Ω, with a 50kHz measurement of 1144Ω. This calculates to an increase in impedance of 21.61% for \( R_0 \), 17.59% for \( R_\infty \), and 19.92% at 50kHz.

For the power setting of 50W with a firing duration of 3s, the prefire Cole-Cole curve had a SEE of 0.66Ω and revealed an \( R_0 \) of 895Ω, an \( R_\infty \) of 598Ω, with a 50kHz measurement of 796Ω. The postfire Cole-Cole curve had a SEE of 1.95Ω and revealed an \( R_0 \) of 1279Ω, an \( R_\infty \) of 730Ω, with a 50kHz measurement of 1014Ω. This calculates to an increase in impedance of 42.91% for \( R_0 \), 22.07% for \( R_\infty \), and 27.39% at 50kHz.
After performing the tests for each power setting and firing durations the $R_0$, $R_\infty$, and 50kHz frequency measurement for each trial was used for analysis. The details of each test are displayed in Figures 3.23-25 respectively. The average of each of the three measurements is plotted, with the error bars representing the maximum and minimum measurement.

![Graph showing Prefire vs postfire percent increase of impedance for $R_0$.](image)

**Figure 3.23. Prefire vs postfire percent increase of impedance for $R_0$.**

Examining the graph for the increase of impedance for $R_0$ shows an upwards trend for increases in both applied power and duration. For the 1s trials, the percent increase for each of the power settings was pretty consistent, with the greatest increase coming from the 50W power setting at 5.41% and the lowest from the 20W power setting at 1.93%. This shows that about the same amount of ECW was lost. For the 3s trial, however, the 50W power setting had an increase of 42.91% with the lowest being that of the 10W power setting with a 9.42% increase. This was shown to be the trend during the perforation measurements as much of the ECW was lost approaching the perforation point.
The percent increase in impedance for $R_{\infty}$ is much different than that of $R_0$. While the spread in the impedance increased for different firing durations for $R_0$, the $R_{\infty}$ values were pretty consistent for each power setting. This is also shown during the perforation tests. While the ECW seemed to be the first to go, the ICW did not differ much until perforation was near.

Figure 3.24. Prefire vs postfire percent increase of impedance for $R_{\infty}$.
Investigating this graph shows a clear upwards trend in the increase in impedance based on the duration of the firing as well as the power setting. For the 1s tests, each of the power settings showed similar minimal increases in the percent of impedance, with the 50W setting having the greatest increase with 7.36%. For the 2s tests, the gap between each power setting starts to increase. The lowest percent increase in impedance was that of the 10W trial with 6.68%, while the largest increase came from the 50W setting with an increase of 19.92%. For the 3s tests, the gap increased further with the 10W trial having an increase in impedance of 10.09% and the 50W trial increasing by 27.39%.

As mentioned before, the 50W, 3s firing duration was deemed to be the limit as perforation ensues. This appears to happen at an increase in impedance of 27.4% while the second highest increase of 24.4% occurs at a power setting of 40W with a firing duration of 3s. With these two trials being the greatest increase in impedance, and knowing the 50W 3s trial caused perforation while the 40W 3s trial did not, a 25% increase in impedance was chosen as the threshold point.

**Figure 3.25. Prefire vs postfire percent increase of impedance at 50kHz**
increase was then programmed into the LabVIEW virtual instrument (VI). The LabVIEW front panel and block diagram are displayed in Appendix C.

Table 3.1 was created to compile the percent increase details side by side for each power setting and firing duration for a clear numerical representation.

Table 3.1. Prefire vs postfire percent increase of impedance

<table>
<thead>
<tr>
<th>Power Setting (W)</th>
<th>Type</th>
<th>1s (%)</th>
<th>2s (%)</th>
<th>3s (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>R₀</td>
<td>4.64</td>
<td>6.33</td>
<td>9.42</td>
</tr>
<tr>
<td></td>
<td>R∞</td>
<td>5.48</td>
<td>7.50</td>
<td>11.65</td>
</tr>
<tr>
<td></td>
<td>50kHz</td>
<td>4.67</td>
<td>6.68</td>
<td>10.09</td>
</tr>
<tr>
<td>20</td>
<td>R₀</td>
<td>1.93</td>
<td>8.54</td>
<td>17.48</td>
</tr>
<tr>
<td></td>
<td>R∞</td>
<td>1.77</td>
<td>10.74</td>
<td>17.25</td>
</tr>
<tr>
<td></td>
<td>50kHz</td>
<td>1.87</td>
<td>8.66</td>
<td>16.93</td>
</tr>
<tr>
<td>30</td>
<td>R₀</td>
<td>4.14</td>
<td>14.13</td>
<td>23.58</td>
</tr>
<tr>
<td></td>
<td>R∞</td>
<td>6.42</td>
<td>12.01</td>
<td>19.25</td>
</tr>
<tr>
<td></td>
<td>50kHz</td>
<td>4.90</td>
<td>12.41</td>
<td>21.06</td>
</tr>
<tr>
<td>40</td>
<td>R₀</td>
<td>3.18</td>
<td>23.13</td>
<td>40.94</td>
</tr>
<tr>
<td></td>
<td>R∞</td>
<td>11.52</td>
<td>10.54</td>
<td>17.31</td>
</tr>
<tr>
<td></td>
<td>50kHz</td>
<td>5.93</td>
<td>14.03</td>
<td>24.42</td>
</tr>
<tr>
<td>50</td>
<td>R₀</td>
<td>5.41</td>
<td>21.61</td>
<td>42.91</td>
</tr>
<tr>
<td></td>
<td>R∞</td>
<td>11.17</td>
<td>17.59</td>
<td>22.07</td>
</tr>
<tr>
<td></td>
<td>50kHz</td>
<td>7.36</td>
<td>19.92</td>
<td>27.39</td>
</tr>
</tbody>
</table>
Impedance Over Time

After implementing the 25% increase in impedance threshold into the VI, multiple tests of the impedance-controlled feedback system were performed for different power settings on the ESU ranging from 10W-50W. During the initial trials, it was found that the firing time of 75ms, found to be the minimum allowed time for the ESU to work properly without showing errors, was too short to apply an effective alternating current to the porcine colon tissue sample. With this short firing time, no thermal damage was being detected, resulting in no change of impedance. To overcome this matter, the firing time was increased to 500ms. With this longer application of alternating current, the thermal damage ensued was detected and measured over time. The results for each test are displayed in Figures 3.26-30. The data points represent the impedance as calculated by LabVIEW and the dotted lines between the data points represent the period of time that the ESU was firing. There are no data points during these times, as no measuring of the DUT takes place during the firing cycle. While measurements of the DUT were taking place, the impedance measured across the reference resistor was monitored and observed to stay within $\pm 5\Omega$ of the ideal $475\Omega$. The solid horizontal line represents the cut-off threshold of the ESU, which is a point defined as a 25% increase from the initial impedance measurement.
For the 10W power trial, the initial impedance was measured to be 1612Ω which corresponds to a cut-off threshold of 2015Ω. The total time, from the beginning of the first firing cycle of the ESU to the first measurement taken above the threshold, took 15.092s. This took completing 22 firing cycles to accomplish with an overshoot of 1.39%.

**Figure 3.26. 10W firing test impedance over time**
The 20W power trial had a starting impedance of 1281Ω with a calculated threshold point of 1601Ω. The elapsed time to reach the threshold point took 11.534s requiring 16 firing cycles with an overshoot of 8.18%.

Figure 3.27. 20W firing test impedance over time

Figure 3.28. 30W firing test impedance over time
With the ESU set to 30W, the trial started with an impedance of 1271Ω resulting in a threshold value of 1589Ω. The time to reach this threshold took 5.994s requiring 9 firing cycles with an overshoot of 0.50%.

![Figure 3.29. 40W firing test impedance over time](image)

The next trial, with a power setting of 40W, took 6.137s to make it from the initial impedance of 1491Ω to the threshold point of 1864Ω while also requiring 9 firing cycles with an overshoot of 11.05%.
With the highest power setting of 50W, the initial impedance was measured to be 1152Ω resulting in a threshold of 1440Ω. While the elapsed time to reach this threshold took 4.123s and required 6 firing cycles with an overshoot of 14.79%.

Figure 3.30. 50W firing test impedance over time
CHAPTER 4

DISCUSSION

Feedback System

After observing the impedance vs time graphs for each of the trials, the alternating current from the ESU was stopped after an increase in impedance of 25% or more was measured. This shows successful implementation and execution of the device as built and programmed.

Further observation of the impedance vs time graphs demonstrate that the impedance measurements drop sharply after the first firing cycle and increase over time. This is thought to occur from the bursting of the cell membranes around where the snare touches the porcine colon sample. During the first firing cycles of each trial, it was visually observed that a small amount of water would pool around the snare. This would lower the impedance as water is a good conductor and the ratio of water to tissue is high. As the firing cycles continued, the water was visually observed to evaporate. As more of the water from the busted cell membranes evaporate, the measured impedance values also increased. This trend continued until the pool of surface water was minimized from the thermal energy being applied. Once this happened, the measured impedance increased beyond the starting impedance and damage to the tissue followed. This thought is further backed by observing the length of time the measured impedance stayed below the initial measurement for each power setting. As the power is increased, the applied current density increases and in turn an increase in the rate of applied thermal energy. First, examine the 10W trial. The measured impedance for this trial stayed below the initial impedance for almost 14s and took 22 firing cycles before reaching the threshold point. For the 20W trial, the time the measured impedance stayed below the initial was only 7s while requiring 16 firing cycles to reach the threshold point. Given a higher applied current density, the increase in thermal energy causes the water from the busted cell membranes to evaporate faster as well as the tissue damage. This trend is further observed for higher power trials. For the
30W and 40W trials, the impedance stayed below the initial measurement for almost 5s with each going through 9 firing cycles. Note that although each of these trials took the same number of firing cycles to reach the threshold point, the 40W trial ended slightly higher above the cut-off point. For the 50W trial, the impedance only stayed below the initial measurement for less than 3s while only requiring 6 firing cycles to reach the threshold point.

Looking closely at the impedance vs time graphs for each trial shows that the impedance threshold point was surpassed. This is evident in the 20W, 40W, and 50W trials with overshoot values of 8.18%, 11.05%, and 14.49% respectively. As the power is increased, the amount of change in impedance for each 500ms firing cycle is increased. For the 20W trial, the last measurement was just below the cut-off point. This resulted in an additional firing cycle that increased the impedance beyond this point. For the 40W and 50W trials, the amount of impedance change per firing cycle was larger than the other trials. This was enough to surpass the threshold level as the measurements before this point was closer to the cut-off point than the increase per firing cycle.

One way to help overcome the problem of high overshoots when operating the feedback system in the future could be the implementation and use of overshoot tolerance bands. The idea of these overshoot tolerance bands would be to monitor when the increase in impedance is getting close to the threshold point, before surpassing it and possibly resulting in a perforation. They could work in a combination of ways. One way could be by turning off the firing operation prematurely if the impedance was measured to be within a certain percentage close enough to the threshold point. This would prevent overshoot from occurring by never letting the impedance actually reach the threshold point. Another way to implement tolerance bands could be to lower the firing duration as the impedance reached closer to the threshold point. The amount the impedance increases each firing cycle is dependent on the duration of applied current. This would reduce the overshoot by reducing the amount the impedance rises between each measuring cycle. These bands could also be adjusted for each power setting. This would also be necessary as the increase in impedance for each firing cycle is different for each power setting. The 10W trial increased less each time the ESU fired than
the 50W trial. This would mean that the overshoot tolerance bands could be closer together for the lower power settings and would be farther apart for the higher power settings. This would ensure that at any power setting, the impedance could increase closer to the threshold value while minimizing as much overshoot as possible.

Limitations

The limitations of this device include the inability to measure the impedance of the sample simultaneously as the ESU is applying current. If this hurdle is crossed, then the device would have the ability to stop closer to the threshold point without going over. Such was the case for the 20W, 40W, and 50W trials. This overshoot in the applied alternating current could in turn cause perforation to occur if it becomes too severe.

Similar Experiments

There have been strides in designing a similar type of auto-stop system that implements impedance measurements using the monopolar method, although this study used the hot biopsy forceps (Tang 2016).
CHAPTER 5

CONCLUSIONS

Objectives

The three main objectives of designing and constructing, testing of proper operation, and verification of the impedance-controlled feedback system have all been accomplished throughout this study. The design and construction objective was solved by soldering together and creating a Howland current pump, active electrodes, gain amplifiers, and multiple relays. Using these built components and integrating them with a power source, function generator, microcontroller, and DAQ accomplished this objective. The second objective of testing the feedback system for the proper operation was solved by using an RRC equivalent circuit in series with a potentiometer, to mimic the increase in impedance of tissue, and using trial and error until the feedback system performed as intended. This was accomplished by creating a LabVIEW VI and Arduino sketch that communicated back and forth and synchronized the safe timing and measuring of the ESU firing and measuring operations which accomplished this objective. The final objective of verification of the feedback system was solved by first ensuring the system was able to turn off the firing from the ESU given a specific impedance threshold, followed by the testing of the porcine colon sample. After the test of the porcine colon was completed, data gathered and analyzed showed that in fact, the impedance-controlled feedback system was working as intended, accomplishing the final objective.

Closing Remarks

The design and implementation of this impedance-controlled hot snare polypectomy device were shown to accurately measure and monitor the change in impedance, with an accuracy of ±5Ω, of a porcine colon sample ex vivo. This allowed for the system to interrupt and stop the high-frequency alternating current from the ESU being applied to the sample before perforation occurred.
This was accomplished by determining when the impedance of the sample had increased from its’ initial measurement by 25%.

While many electrosurgical device manufacturers have some version of an auto-stop system built in, the downside to these devices, however, is the fact that the auto-stop systems are usually directed towards the bipolar method and with the use of forceps. The advantage of the impedance-controlled feedback polypectomy device in this study is the ability to auto-stop using the monopolar method with a snare. This is important due to the fact that most polyps are classified as either small or diminutive, with snare polypectomy being the preferred method to remove these size polyps. While the experience of the surgeon is a main contributing factor for complications such as perforation to occur, this auto-stop system should help to minimize excess thermal injury incurred by the patient. This device should allow the surgeon to perform their job more safely and with higher confidence. And in turn, lead to fewer complications during surgery with higher success rates.

The intent of this impedance-controlled device is such that it be used as an add-on device or accessory to complement the current device a surgeon may have. If the foot pedal assembly is similar to that of the PSD-30’s, then this device has the capability to work. This will keep the cost down for the surgeon, as there is no need to purchase another ESU, and ultimately the patient. It also allows for the use of the current and preferred snares and ground patches, so no additional or new accessories are required to purchase.

In the future, we hope to gather in vivo data about the impedance values of various polyps during different times including before, during, and right before the removal of the polyp. This will allow for a better understanding of how the impedance changes of the polyp in a more realistic setting. With this data, the impedance-controlled device can be further programmed to overcome any previously unforeseen situations.
REFERENCES


APPENDIX A
ARDUINO SKETCH USED TO CONTROL THE TIMING

/*
Description: This program is used to control the interaction between the foot pedals of the
PSD-30 ESU and LabVIEW; to control the timing of the measurements and firing of the ESU.
Created by: CurtisLee Thornton
Last revision date: 6-11-2019
*/

const int coagSignal = 2;
const int coagFire = 3;
const int cutSignal = 4;
const int cutFire = 5;
const int measureRelay = 8;
const int snareRelay = 9;
const int daqSignal = 11;
const int interruptPin = 12;
const int fireTime = 500; //miliseconds
const int delayTime = 25; //miliseconds
volatile byte flag = 1;

class Controller {
    int firePin;

public:
    Controller(int pin) {
        firePin = pin;
    }
}
void Fire() {
    digitalWrite(daqSignal, LOW);
delay(delayTime);
download(measureRelay, LOW);
delay(delayTime);
download(snareRelay, HIGH);
download(firePin, HIGH);
delay(fireTime);
download(firePin, LOW);
download(snareRelay, LOW);
delay(delayTime);
}

Controller coag(coagFire);
Controller cut(cutFire);

void setup() {
  Serial.begin(9600);
pinMode(coagSignal, INPUT);
pinMode(cutSignal, INPUT);
pinMode(snareRelay, OUTPUT);
pinMode(measureRelay, OUTPUT);
pinMode(interruptPin, INPUT);
pinMode(daqSignal, OUTPUT);
}

void Measure() {

void stopAll() {
  flag = 0;
}

void loop() {
  digitalWrite(measureRelay, LOW);
  digitalWrite(daqSignal, LOW);
  digitalWrite(snareRelay, LOW);
  digitalWrite(coagFire, LOW);
  digitalWrite(cutFire, LOW);
  Serial.println("outside WHILE");
  delay(1);
  while (true) {
    if (digitalRead(coagSignal) == HIGH && flag == 1) {
      coag.Fire();
      Measure();
      if (digitalRead(interruptPin) == HIGH) {
        stopAll();
      }
    } else if (digitalRead(cutSignal) == HIGH && flag == 1) {
      cut.Fire();
      Measure();
      if (digitalRead(interruptPin) == HIGH) {
        }
    stopAll();
    }
} else {
    Serial.println("ELSE measuring");
    digitalWrite(coagFire, LOW);
    digitalWrite(cutFire, LOW);
    digitalWrite(snareRelay, LOW);
    delay(delayTime);
    Measure();
    }
}
APPENDIX B
MATLAB SCRIPT USED FOR DATA ANALYSIS

% close all; clear; clc;

% Range of numbers to plot
% Column - 1:freq; 2:Z; 3:phase; 4:resistance; 5:reactance
% Row - 22:3kHz; 115:25kHz; 145:50kHz; 246:500kHz; 277:1MHz

fullRange = 'A22:E277'; % 3kHz-1MHz
filterRange = 'A115:E246'; % 25kHz-500kHz

div = 9; % Plot every division point
errorType = 0; % Enter '0' for SEE or '1' for average

% Read in files

folderName = '"C:\Users\ct05456\Desktop\impedimed output 6-3-19\excel"';

highName = 't4-0000';
midName = 't4-0001';
lowName = 't4-0002';

fileNameHigh = strcat(folderName,highName,'.xls');
highFile = xlsread(fileNameHigh,filterRange);
highRange(:,1) = highFile(:,4);
highRange(:,2) = highFile(:,5);

fileNameMid = strcat(folderName,midName,'.xls');
midFile = xlsread(fileNameMid,filterRange);
midRange(:,1) = midFile(:,4);
midRange(:,2) = midFile(:,5);

fileNameLow = strcat(folderName,lowName,'.xls');
lowFile = xlsread(fileNameLow,filterRange);
lowRange(:,1) = lowFile(:,4);
lowRange(:,2) = lowFile(:,5);

% Find averages
resistanceArray(:,1) = highRange(:,1);
resistanceArray(:,2) = midRange(:,1);
resistanceArray(:,3) = lowRange(:,1);
avgResistance = mean(resistanceArray,2);

reactanceArray(:,1) = highRange(:,2);
reactanceArray(:,2) = midRange(:,2);
reactanceArray(:,3) = lowRange(:,2);
avgReactance = mean(reactanceArray,2);

averageArray = [avgResistance,avgReactance];

% Modify number of data points

cnt = 1;
for ii = 1:length(averageArray(:,1))
    if mod(ii,div) == 0
        averageArrayMod(cnt,1) = averageArray(ii,1);
        averageArrayMod(cnt,2) = averageArray(ii,2);
        lowRangeMod(cnt,1) = lowRange(ii,1);
        lowRangeMod(cnt,2) = lowRange(ii,2);
        highRangeMod(cnt,1) = highRange(ii,1);
        highRangeMod(cnt,2) = highRange(ii,2);
        cnt = cnt + 1;
    end
end
function [r0, rinf, cir, SEE] = ccplotSEE(avg, avgMod, low, high, errorType)
% this function takes in the resistance and reactance values and plots the
cole-cole curve, it then fits a circle to the data and provides some
information on where the circle crosses the x-axis (r0 and rinf) and it's center
% location

% Error bar range
xLow = abs(avgMod(1,:)-low(1,:));
xHigh = abs(high(1,:)-avgMod(1,:));
yLow = abs(avgMod(2,:)-low(2,:));
yHigh = abs(high(2,:)-avgMod(2,:));

% Plot data
hold on
xlabel('Resistance (\Omega)');
ylabel('Reactance (\Omega)');
% Circle fit
% https://www.mathworks.com/matlabcentral/fileexchange/22643-circle-fit--pratt-methodcir1=
cir = CircleFitByPratt(avg);
xCenter = cir(1);
yCenter = cir(2);
radius = cir(3);
theta = 0 : 0.01 : 2*pi;
x = radius * cos(theta) + xCenter;
\[ y = \text{radius} \times \sin(\theta) + y_{\text{Center}}; \]
\[ \text{plot}(x, y); \]

\% Get SEE
\[ \text{err} = \text{zeros}(1, \text{length(avg(:,1))}); \]
\[ \text{neg} = \text{find}(y < 0); \]
\[ x(\text{neg}) = []; \]
\[ y(\text{neg}) = []; \]
\[ \text{for kk = 1:length(avg(:,1))} \]
\[ \ \ \ y_{\text{circ}} = \text{interp1}(x, y, \text{avg}(kk,1)); \]
\[ \ \ \ \text{if} \ \ \ \neg\text{isnan}(y_{\text{circ}}) \]
\[ \ \ \ \ \ \ \ \text{err}(\text{kk}) = (\text{avg}(kk,2) - y_{\text{circ}})^2; \]
\[ \ \ \ \text{end} \]
\[ \text{end} \]
\[ \text{SEE} = \sqrt{\text{sum(err)/length(err)}}; \]

\% Find where circle crosses x-axis
\[ r_0 = \sqrt{(\text{radius}^2 - (y_{\text{Center}}^2)) + x_{\text{Center}}}; \]
\[ r_{\text{inf}} = -\sqrt{(\text{radius}^2 - (y_{\text{Center}}^2)) + x_{\text{Center}}}; \]

\% Plot center and set axis limits
\[ \text{axis equal}; \]
\[ \text{grid on}; \]
\[ \text{plot}(x_{\text{Center}}, y_{\text{Center}}, '+'); \]
function Par = CircleFitByPratt(XY)

% Circle fit by Pratt
% V. Pratt, "Direct least-squares fitting of algebraic surfaces",

% Input: XY(n,2) is the array of coordinates of n points x(i)=XY(i,1), y(i)=XY(i,2)
% Output: Par = [a b R] is the fitting circle:
% center (a,b) and radius R

% Note: this fit does not use built-in matrix functions (except "mean"),
so it can be easily programmed in any programming language

% computing moments (note: all moments will be normed, i.e. divided by n)

n = size(XY,1);  % number of data points

centroid = mean(XY);  % the centroid of the data set
Mxx=0; Myy=0; Mxy=0; Mxz=0; Myz=0; Mzz=0;

for i=1:n
    Xi = XY(i,1) - centroid(1);  % centering data
    Yi = XY(i,2) - centroid(2);  % centering data
    Zi = Xi*Xi + Yi*Yi;
    Mxy = Mxy + Xi*Yi;
    Mxx = Mxx + Xi*Xi;
    Myy = Myy + Yi*Yi;
    Mxz = Mxz + Xi*Zi;
    Myz = Myz + Yi*Zi;
    Mzz = Mzz + Zi*Zi;
end

Mxx = Mxx/n;
Myy = Myy/n;
Mxy = Mxy/n;
Mxz = Mxz/n;
Myz = Myz/n;
Mzz = Mzz/n;

% computing the coefficients of the characteristic polynomial

Mz = Mxx + Myy;
Cov_xy = Mxx*Myy - Mxy*Mxy;
Mxz2 = Mxz*Mxz;
Myz2 = Myz*Myz;

A2 = 4*Cov_xy - 3*Mz*Mz - Mzz;
A1 = Mzz*Mz + 4*Cov_xy*Mz - Mxz2 - Myz2 - Mz*Mz*Mz;
A0 = Mxz^2*Myy + Myz^2*Mxx - Mzz*Cov_xy - 2*Mxz*Myz*Mxy + Mz*Mz*Cov_xy;
A22 = A2 + A2;

epsilon=1e-12;
ynew=1e+20;
IterMax=20;
xnew = 0;

for iter=1:IterMax
    yold = ynew;
    ynew = A0 + xnew*(A1 + xnew*(A2 + 4.*xnew*xnew));
    if (abs(ynew)>abs(yold))
        disp('Newton-Pratt goes wrong direction: |ynew| > |yold|');
        xnew = 0;
        break;
    end
    Dy = A1 + xnew*(A22 + 16*xnew*xnew);
    xold = xnew;
    xnew = xold - ynew/Dy;
    if (abs((xnew-xold)/xnew) < epsilon), break, end
    if (iter >= IterMax)
        disp('Newton-Pratt will not converge');
        xnew = 0;
    end
    if (xnew<0.)
        fprintf(1,'Newton-Pratt negative root: x=%f\n',xnew);
        xnew = 0;
    end
end
end

% computing the circle parameters

DET = xnew*xnew - xnew*Mz + Cov_xy;
Center = [Mxz*(Myy-xnew)-Myz*Mxy , Myz*(Mxx-xnew)-Mxz*Mxy]/DET/2;

Par = [Center+centroid , sqrt(Center*Center'+Mz+2*xnew)];

end % CircleFitByPratt
APPENDIX C

LABVIEW VI FRONT PANEL AND BLOCK DIAGRAM