Finger Plethysmograph to Measure Blood Resistivity

Tim Balgemann, Sarah Offutt, Lucas Vitzthum, and Josh White

Abstract- **Impedance plethysmography can be used to measure arterial volume change that occurs with propagation of the blood pressure pulse in a limb segment. For this measurement, we assume a constant value of blood resistivity that may change under both physiological and pathological conditions. Our research is to determine if an impedance plethysmograph on a finger immersed in a saline filled beaker can yield a method for measuring this change in blood resistivity. This method may be developed into a noninvasive technique to measure glucose levels in diabetics.**

`*Index Terms*— **Blood resistivity, diabetes, impedance plethysmography,**

I. INTRODUCTION

Diabetes is a disease characterized by the body's inability to manage glucose levels. It is a chronic condition caused by the pancreas's lack of ability to produce enough insulin or the failure of the body to effectively use the insulin produced. The prevalence of diabetes is astounding; in the United States there are 17.9 million diagnosed cases of diabetes and it is estimated that there are an additional 5.7 million undiagnosed individuals living with the disease [1]. The disease is also on the rise; over the last three years, the number of diagnosed individuals has risen 13.5 percent. Globally, occurrence rates of diabetes are even higher; at least 171 million people worldwide have diabetes [2]. In addition to the large number of people living with the disease, the direct and indirect costs of diabetes are strong motivators for improving methods for monitoring blood glucose levels.

There is an interest to quantify electrical impedance and consequently the resistivity change due to blood flow. During high blood flow, such as when the blood pulses through the finger, red blood cells (RBCs) align and decrease the resistance to electrical current (fig. 1). During lower blood flow the RBCs tend to clump together or misalign (fig. 1). In this situation, current meets more opposition to flow and as a result the impedance increases. It is hypothesized that blood resistivity will change with varying blood glucose levels. Higher levels of glucose in the blood would also result in greater clumping of RBCs and a higher resistivity. One of the

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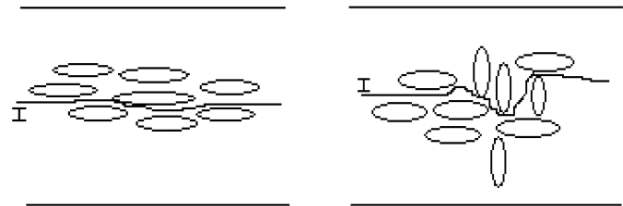
Fig. 1. Differences in RBC alignment. (1) RBCs are aligned during high blood flow. (2) RBCs are misaligned during low blood flow

goals is to be able to correlate these different impedance and resistivity measurements with varying glucose levels [3].

Four electrode impedance plethysmography will be used to monitor blood resistivity. Two electrodes are used to pass current through the finger and two electrodes are used to measure the voltage drop across the finger. For this project, the finger will be inserted downward into a tube. The two outermost electrodes inject current and the two central electrodes measure the voltage across the middle section of the finger. By passing current through the finger (which provides resistance), the resulting voltage drop can be measured across these electrodes [4].

The voltage measurements will vary depending upon physiological changes in the blood and due to the blood pulse itself. It is expected that these measurements will be small. In order to observe and analyze the signal obtained from the middle electrodes, the voltage output is passed to a circuit that amplifies and processes the signal. This output signal can be used to calculate the impedance and resistivity of the blood in the finger. It is hypothesized that the resistivity can be correlated with different blood compositions.

Current blood glucose monitors require a small sample of the patient's blood in order to determine glucose levels. This is attained through a painful, self-induced finger prick using a lancet. The blood sample is then placed on a test strip, which is inserted into the blood glucose meter and the meter then provides a digital readout of the amount of glucose in the blood. Because of the associated inconvenience and pain of these methods, a simple, more user-friendly, non-invasive method is desired.

II. MATERIALS AND METHODS

A. Constraints

The finger impedance plethysmograph was designed to meet the following constraints. As the device requires a patient-

electrical interface, the primary design constraint is safety. The electrical circuitry going to and from the finger holder and electrodes must be electrically isolated from the rest of the circuit and the entire prototype must be completely electrically insulated. The device should be designed to accommodate a wide range of finger sizes while restraining the finger to reduce motion artifacts. Lastly, the device is being designed for a clinical testing environment. Accordingly it should be easily operated by a trained medical professional.

B. Device Design

This device has to major components, 1) the circuit and 2) the finger holder. The two components were developed and tested in order to optimize device output.

1) Circuitry

The voltage signals from across the finger are expected to be very small and could be buried within a substantial amount of noise. Therefore the circuit is designed to amplify the small voltage difference across the finger and to filter noise that corrupts the signal. The extremely small nature of the signals being measured requires high gain amplification. To eliminate the problem of amplifier saturation due to motion artifacts, the circuit contains an automatic reset and sample and hold module. The signals being measured have a substantial amount of common interference that does not need to be amplified. To focus solely on the changing signal, a differential amplifier is used. To address these needs, the final circuit design consists of six modules that have been designed specifically to measure the signals from the finger holder. These six modules are differential pre-amplification, rectification, sample and hold, automatic reset, high gain differential amplification, and filtering and signal processing (fig. 2).

The constant current source supplies current to the two current electrodes in the finger holder at a frequency of 10 kHz. The current amplitude ranges from 1 to 5 mA peak to peak, dependent on the finger holder being used. The current source consisted of an LMC741 op-amp with a 1.2KΩ resistor at the inverting terminal. Both amplifier stages employ AD620 instrumentation amplifiers. The preamp gain was set at 19 V/V while the high gain amp was set at 100 V/V. The signal is amplified by the pre-amplification stage and sent to a rectifier stage. The rectifying stage uses a 1N4001 diode to create a half-wave rectifier with a ripple to peak ratio of .1V/mV. This stage results in a DC signal which contains the low frequency changes in voltage that are to be further amplified.

The reset circuit consisted of a window comparator with a window set at ±9.35 volts. LM339 comparators were used to construct the window. When the output voltage exceeds +9.35 volts or drops below -9.35 volts the comparator output is -12 volts. This causes the 555 timer to output a voltage pulse with amplitude of 8 volts for a duration of 0.1 seconds. This pulse turns on the MOSFET and enables it to sample the rectifier output.

The sample and hold circuit consists of a 2SK3767 n-type MOSFET and a TL084CN op-amp. The MOSFET operated as

a voltage controlled switch which closes when the output exceeded ±9 volts. This causes an electrolytic capacitor to charge to the voltage sampled from the rectifier output and hold this at the inverting input of the high gain amplifier. This sequence returns the output to zero, compensating for motion artifacts.

The final filtering stage is done both in the circuit and digitally once results were collected. The physical filtering is done with a low pass filter. The digital filtering will be discussed in the analysis and results section.
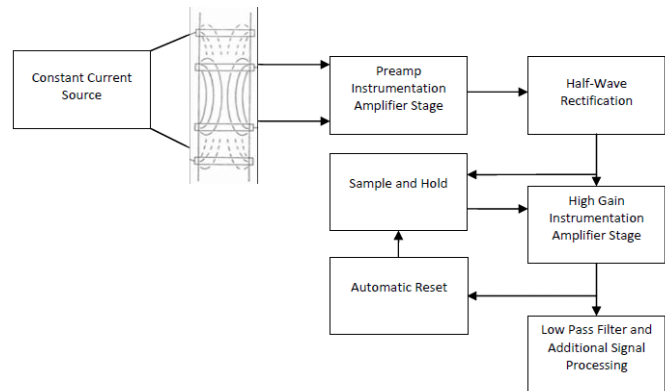

Fig. 2. Final block diagram showing the constant current source, electrode configuration and signal pathway

2) Finger Holder

Two generations of the finger holder were built and tested. Both generations were built with Sch. 40 PVC as the outer tube, three elastomeric foam cuffs, and four tin electrodes. The only difference in the two designs was the diameter of the holder. The first generation was built with 1.5" diameter PVC whereas the second generation was build with 1" diameter.

The elastomeric foam was included to add comfort to the design and to stabilize the finger for testing. Three cylindrical sections of foam were attached to the tube: one section at the bottom to stabilize the finger tip, one stabilizing the proximal interphalangeal joint, and the other at the top opening of the tube to stabilize the proximal phalange. These cuffs accommodate a wide range of finger tip and base sizes. This design allows for the ability to perfectly match the restraint size to the subject's finger size.

The electrodes were made from tin defibrillator electrodes. Each electrode was .5" wide and completely wrapped around the inner circumference of the tube. The electrodes were spaced in the tube such that the current ground electrode was at the bottom of the tube and the current input electrode was directly underneath the first foam stabilizer. The top voltage electrode was placed directly below the current input electrode. The bottom voltage electrode was placed immediately under the proximal interphalangeal joint-stabilizing foam. The ground electrode was modified from the original ring to a circular plate measuring 1" in diameter and attached perpendicularly to the long axis of the tube. Each electrode had a wire soldered to it, which was run up the inner wall of the tube to exit out the top. The bottoms of the tubes were sealed with an appropriate Sch. 40 PVC end cap.

If the finger is surrounded by isotonic saline (0.9% NaCl), the saline acts to cancel any signal generated by the volume change of the arteries during a pulse. During a pulse, an amount of saline equal to that of the pulse volume is displaced in the finger holder. The saline produces a signal that is equal and opposite to that of the signal from the volume change of the blood vessel. Thus, the signal generated from the volume change of the vessel does not interfere with the small change in resistivity trying to be obtained [5].

Final testing was done with the second generation, because, as hypothesized, the current was focused more through the finger than the saline solution due to the smaller diameter. In addition, an armrest was created for testing to further reduce motion artifacts. The armrest was built so that when the test subject is seated their arm rests comfortable and their finger is inserted at the appropriate angle into the finger holder. Attached to arm rest is a stabilizer for the finger holder.

III. DATA AND ANALYSIS

A. Finger Model

In order to test the efficacy of our circuit, we created a 'phantom circuit' to mimic the expected electric characteristics of the finger. Shankar et al. calculated that the expected impedance change from a change in blood flow to be 1/1000 the size of the DC impedance caused by skin, fat, saline, etc. Therefore, we constructed a passive circuit that mimics this 1/1000 impedance change using two resistors connected in parallel through a switch.

The output of our circuit shows a voltage change of approximately 0.15 V when the phantom circuit is used as an input (fig. 3.). These results demonstrate that the circuit can amplify the expected size of the signal as well as pass physiologically relevant signals at frequencies near 1Hz. It is also evident that there is a small drift in the system likely caused by capacitor leakage.
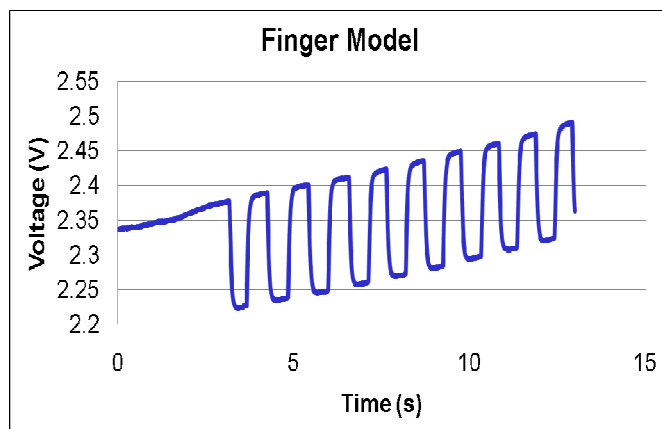

Fig. 3. Output of circuit when connected to electrical finger model simulating a 1/1000 impedance change.

B. Human Testing

In this study we focused on identifying a pulsatile signal caused by the varying impedance from blood flow. Signals were acquired for 10-30 seconds from the impedance plethysmograph, as well as a commercial pulse oximeter, (fig. 4). In order to reduce uncontrolled variables, the same 22 year old male subject was used in all studies. Measurements were recorded using NI Elvis digital interface breadboard and custom LabView software. The pulse oximeter serves as a positive control in identifying the pulsatile signal from the heart beat. This signal helps identify the frequency of the heart beat in the spectral domain. The output signals from the finger plethysmograph and the pulse oximeter appear to have an aligned periodicity (fig. 4, fig. 7). This alignment is further analyzed by using a Fourier transform to view the signals in the frequency domain (fig. 5, fig. 8). The highlighted region (~.9 Hz or 54 BPM) of the spectral graph of fig. 5 shows an alignment of frequencies of the plethysmograph with pulse oximeter signals. The presence of a corresponding spectral peak to the pulse oximeter may signify a periodic component from the heart beat present in the plethysmograph signal. Frequency components from 0.5 -1.5 Hz were amplified by a factor of 3 and frequency components from 0-0.4 Hz were attenuated by a factor of 10 in order to clarify the signal of interest (fig. 6). The filtered signal further makes a correlation apparent between the periodicity of the pulse oximeter and plethysmograph signals.

A negative control was conducted in which the change in impedance from blood flow was removed from the plethysmograph signal by occluding the subject's brachial artery. Identical frequency analysis and filtering was performed on the negative control signals (fig. 7, fig. 8, fig. 9). In the frequency domain, there is a noticeable lack of a periodicity in plethysmograph signal. Futhermore, there is no significant peak in the expected 1 Hz range of the frequency domain signal (fig. 8).

III. RESULTS AND DISCUSSION

From testing the finger model, it was shown that the circuit built could effectively amplify and rectify a changing voltage caused by a 1/1000Ω resistance change. When the switch of the finger model was depressed, a 200mV voltage change resulted. This voltage change, while relatively small, is large enough to be accurately measured and studied. These tests confirmed that the circuit was functioning as predicted and that it could be used in conjunction with the plethysmograph. As noted above, the output had a 20mV/sec drift. This drift was the result of the sample and hold capacitor leaking charge slowly through the op-amp buffer. As of now this drift does not interfere with the data collection, but for future use in glucose measurement this drift will need to be minimized or eliminated.

Testing was performed on both generations of the finger holder prototype. The results from the tests done on the first generation (figures omitted) showed that a larger amount of current (5mA) was needed to produce a measurable signal. However, this signal revealed very little correlation to the pulse oximeter signal. When the same tests were performed on the second generation finger holder, a much smaller current (2.58mA) was needed to produce a sensitive and measurable
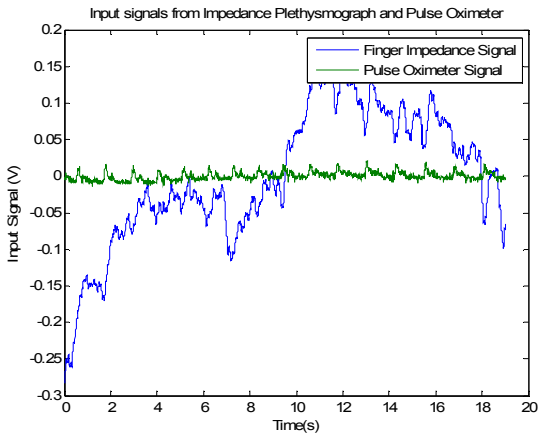
Fig. 4. Non-occluded raw data. Output from our finger plethysmograph and a pulse oximeter (positive control signal). Signals were sampled at 1kHZ. Both signals were normalized to zero.
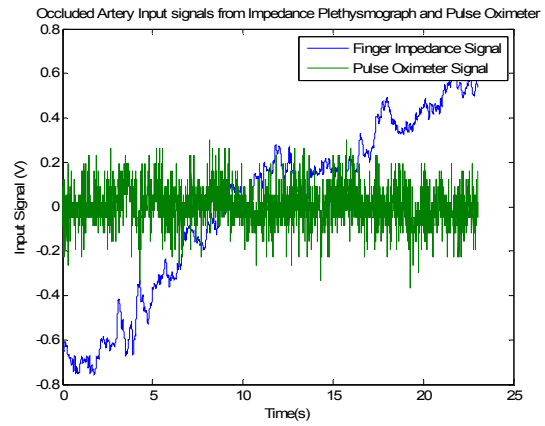

Fig. 7. Occluded raw data. Output from our finger plethysmograph and a pulse oximeter. Signals were sampled at 1kHZ. Both signals were normalized to zero.
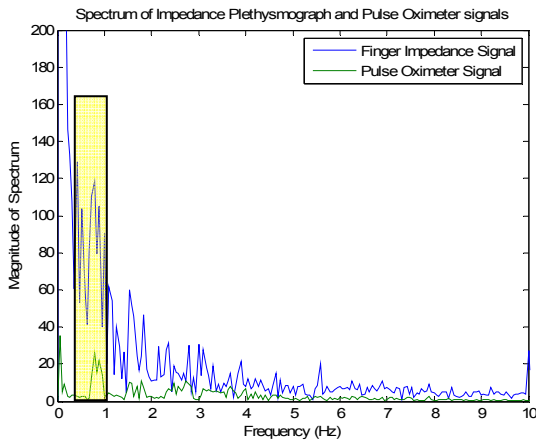

Fig. 5. Non-occluded spectrum. Spectrum of the signal (DC components of both spectrum are eliminated in the adjusted signal). There are two peaks aligned at ~1 that is likely cause by heart beat.
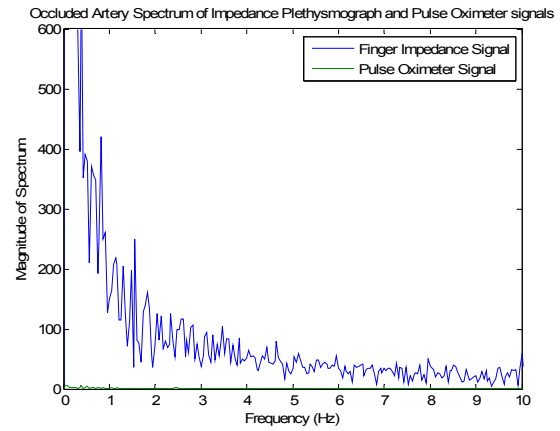

Fig. 8. Occluded spectrum. Spectrum of the signal (DC components of both spectrum are eliminated in the adjusted signal).
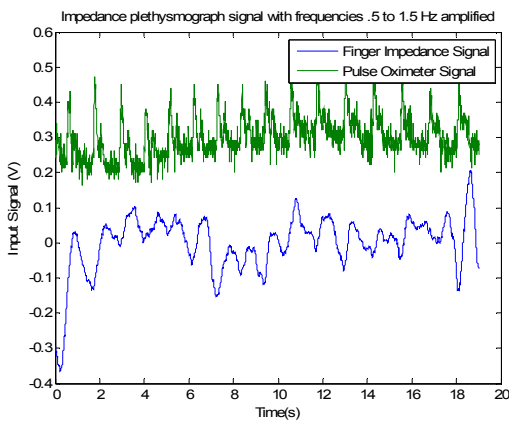

Fig. 6. Non-occluded filtered signal. The signal is boosted from 0.8-1.5 Hz frequencies by a factor of 3. Low frequency signals < |.2 Hz| are attenuated by a factor of 10. Heart beats appear apparent in both.
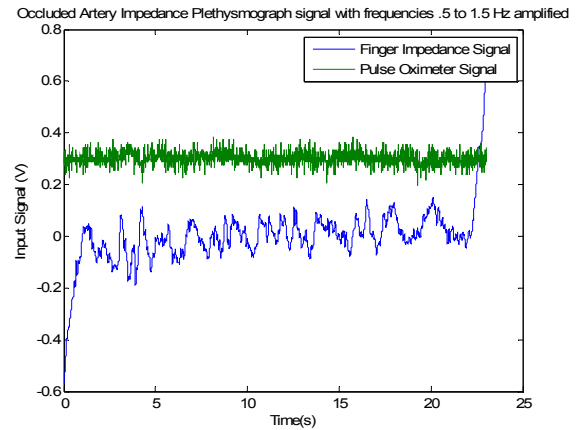

Fig. 9. Occluded filtered signal. Filtered output from our finger plethysmograph and a pulse oximeter.

signal. The difference was attributed to the idea that a majority of the current supplied to the electrodes did not pass through the finger, but instead passed through the saline surrounding the finger. The first generation finger holder used a larger diameter tube of 1.5''as compared to the 1'' diameter of the second generation. The use of a smaller diameter tube focused more of the current through the finger due to the smaller volume of saline. One drawback, that must be investigated, is the affect of the saline decrease on the devices ability to cancel out signals developed by the volume dependant resistance changes.

The second generation finger holder provided the best results during testing. The raw data from the device showed a correlation between the low dips and the peaks of the pulse oximeter signal. This decrease in voltage with each heart beat matches the results observed with the finger model. This correlation validated the results gathered from the finger holder testing. The results from the brachial artery occlusion tests showed that when the blood flow was stopped with an inflated blood pressure cuff the correlating peaks and troughs between the pulse oximeter and plethysmograph signal disappeared. This further supports the claim that the troughs present in the non-occluded test are caused by the changing resistance of the vessel with each pulse of blood.

One aspect of the design was not tested during these trials, this being weather the saline had done an efficient job canceling out the volume dependent resistance changes. Because of this we are unable to state that the changes in voltage reported are caused solely by the hypothesized blood cell orientation and clumping, but most likely a combination of this and blood vessel volume changes. Additional testing is needed to discern between these two sources of resistance change.

From the testing done on the circuit and finger model prototypes it has been shown that impedance plethysmography of the finger may be a method for determining resistance changes in the blood. The results from these trials show that the current design is adequate enough to detect the change in resistance in the finger when the heart pumps blood through it; however additional improvements and testing are necessary to focus in on the resistance change due to blood cell alignment. Once this is done clinical trials can be performed to determine if the blood resistivity can be used to determine a persons blood glucose levels.

REFERENCES

[1] American Diabetes Association. *Total Prevalence of Diabetes & Pre-diabetes.* http://www.diabetes.org/diabetes-statistics/prevalence.jsp. Accessed 10/14/08.
[2] World Health Organization *Diabetes.* http://www.who.int/dietphysicalactivity/publications/facts/diabetes/en/. Accessed 10/14/08.
[3] Webster J.G. Personal communication during team meeting. 9/10/08.
[4] Webster J.G. 1998. *Medical Instrumentation: Application and Design* (3rd ed.). Webster J.G. (Ed). New York: John Wiley & Sons.
[5] Shankar, R. Noninvasive Means to Detect Acute Hyperglycemia and Hypoglycemia in a Child.

A Finger Plethysmograph to Measure Blood Resistivity

Team Members: Tim Balgemann, Sarah Offutt, Lucas Vitzthum, Josh White

Function: Our goal is to design a finger plethysmograph to measure blood resistivity. Impedance plethysmography may be used to measure arterial flow change that occurs with propagation of the blood pressure pulse in a limb segment. For this measurement, we assume a constant value of blood resistivity that will change under dynamic and static conditions. However, blood resistivity and flow conditions may change under both physiological and pathological conditions. Use of an impedance plethysmograph on a finger immersed in a salt filled beaker may yield a simple method for determining blood resistivity. This may develop into a method that diabetics can use to measure glucose level noninvasively.

Client requirements: (itemize what you have learned from the client about his / her needs): Briefly describe, in bullet form, the client needs and responses to your questions.

- The device must observe the change in impedance caused by pulsatile blood flow
- The device must meet all Institutional Review Board (IRB) requirements, so that it may be used in a clinical trial.
- The device should employ an automatic reset function to compensate for motion artifacts.

Design requirements: This device description should be followed by list of all relevant constraints, with the following list serving as a guideline. (Note: include only those relevant to your project):

1. **Physical and Operational Characteristics**
   a. *Performance requirements*: Initially, this device is intended to be used in a clinical research setting. Accordingly, it must be intuitive and easy to use for a trained medical professional. The data output must be reliable, and easy to read with a user friendly interface.

   b. *Safety*: The device will be designed so that the electricity used will not cause any harm to the user. Electrical exposure is limited to the finger, so no current should ever flow through the heart. The American Heart Association recommends that no more than 10 μA RMS current be applied across the chest. Because our device exceeds this limit, it is important that the device is thoroughly electrically insulated such that no alternative current route is made through the body. (www.americanheart.org) . Proper labeling must be used to ensure the patients and clinicians are aware of the dangers involved with applying an electrical current to the body. The safety standards employed in this device should meet Institutional Review Board's regulations.

   c. *Accuracy and Reliability*: Current home blood glucose meters' test results are considered 'accurate' if they falls within +/–20% of an accepted reference result, usually a lab test1. Although this seems like a high margin of error, our design is by definition going to be less accurate than current blood drawing methods, so exceeding their accuracy is unlikely. To compensate for motion artifacts, the device should use an automatic reset function.

   d. *Life in Service*: The device should be operable for a period of up to 6 months or until the completion of the necessary testing and evaluation of the prototype can be completed. The device should be able to provide consistent results over an entire research trial with run times of up to 5 consecutive hours. The device should be able to withstand minor physical impact such as being dropped from a height of 1 meter.

   e. *Shelf Life*: The device should be able to withstand a shelf life of up to 3 years if kept in a 10-35º C low humidity environment. The saline solution should be made fresh daily to prevent changes in salinity from evaporation.

   f. *Operating Environment*: This device will be used in a clinical and laboratory setting. It will likely be in a controlled temperature, humidity and light environment. The lab will most likely have other instrumentation instruments, so the device will likely be subjected to electrical interference. This device should employ some means of reducing electromagnetic interference to the signal.

   g. *Ergonomics*: The device must be able to accept a wide range of finger sizes, while minimizing finger mobility. The user must be able to easily

insert their finger into the device with their finger and fore arm comfortably yet firmly restrained.

h. *Size*: The devices size must be such so that it doesn't interfere with the positioning of the finger and it can't hinder the data collection, but size is not a critical design constraint in this clinical setting

i. *Weight*: The prototype designed for clinical setting does not need to be overly light. It must be under 25 pounds so any personal can move it without assistance.

j. *Materials*: Materials must be corrosion resistant, as they will be exposed to a saline solution for an extend period of time. All non electrical components must be insulating, so that no other points of electrical contact are made with the body.

k. *Aesthetics*: Color, shape, form, texture of finish should look professional yet non intimidating to ensure both physicians and patients feel comfortable with the device.

2. **Production Characteristics**
    a. *Quantity*: We will initially construct 2-3 devices to be used in research.

    b. *Target Product Cost*: The current device is being designed for a research environment where low cost is not a high priority.

3. **Miscellaneous**
    a. *Standards and Specifications*: Must meet all Institutional Review Board Requirements for clinical trials. Exact specifications can be found at http://www.grad.wisc.edu/research/hrpp/hsirbs/hs.ForIRBMembers.html .

References:
1. Defined by the error-grid analysis method of Clarke WI., et al. In "Evaluating Clinical Accuracy of Systems for Self-Monitoring of Blood Glucose," *Diabetes Care*, Vol. 10, No. 5 (1987), 622–628.
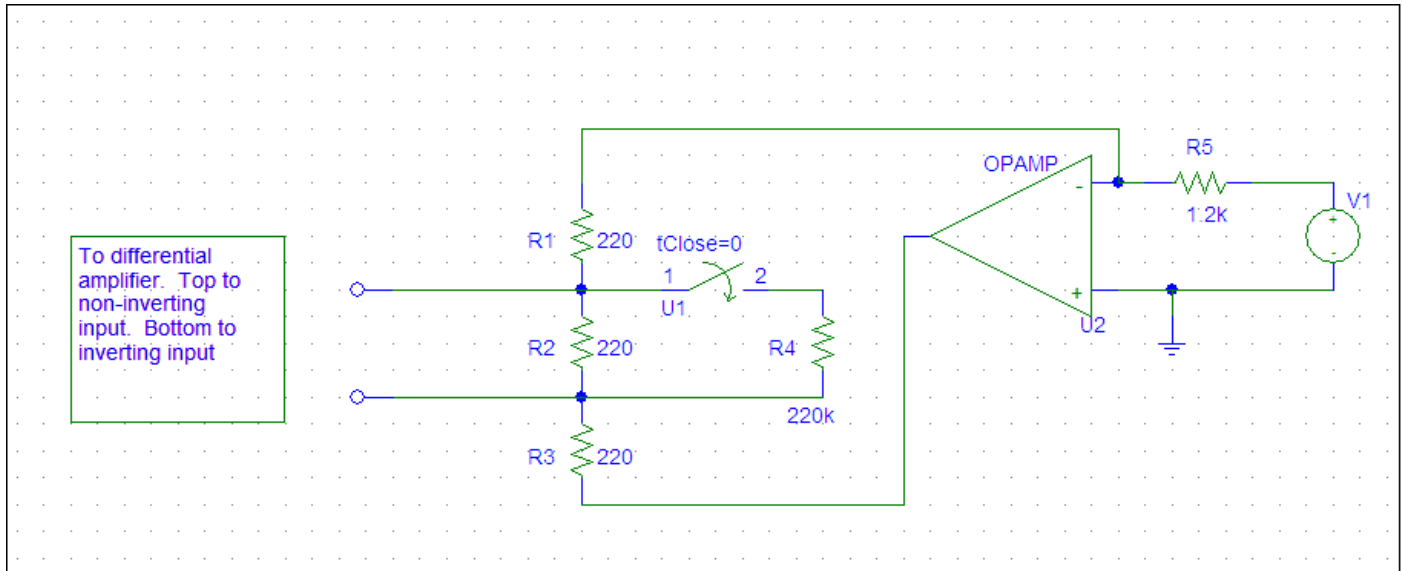
APPENDIX B – CIRCUIT DESIGN

Schematic of the circuit used to amplify, rectify and filter the signal received from the finger holder. This schematic also shows how the sample and hold circuit is incorporated.
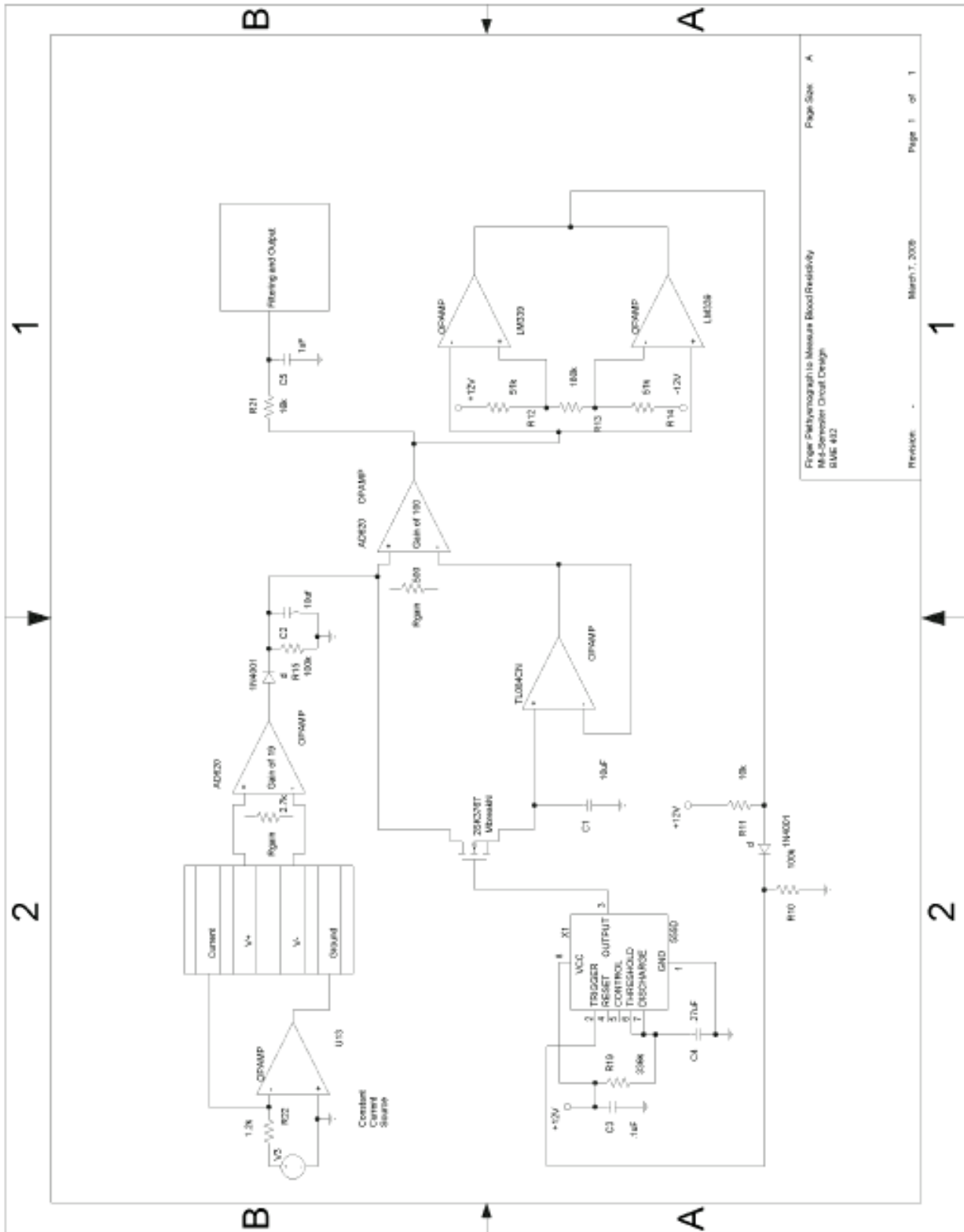
APPENDIX C – FINGER MODEL CIRCUIT

Schematic of finger model circuit used to mimic the small
change seen in the finger.

APPENDIX D – FINGER HOLDER DRAWING

The drawings below are the finger holder from the outside on
the left and an inside view on the right

Foam
Insulator

Electrode