Impedance Cardiography

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Table of Contents

I. Problem Statement

Impedance cardiography is a medical procedure utilized in order to noninvasively analyze and depict the flow of blood through the body[2]. Traditionally, four electrodes are attached to the body, two on the neck and two on the chest, which take beat by beat measurements of blood volume and velocity changes in the aorta. However, this system suffers from degrees of inaccuracy, possibly due to the fact that the electrodes are placed too far from the heart[1]. As a result, it is our collective goal to design an accurate, reusable, and spatially specific impedance cardiograph system that ensures accurate and reliable readings.

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II. Background:

It is frequently necessary in the hospital setting to assess the state of a patient's circulation. Here the determination of simple measurements, such as heart rate and blood pressure, may be adequate for most patients, but if there is a cardiovascular abnormality then more detailed approach is needed[3]. In order to non-invasively gather specific measurements on the volume of blood pumped by the heart (cardiac output) through the aorta, the technique of cardiography can be used. Cardiographic measurements are useful both in establishing a patient's initial cardiovascular state and in measuring one's response to various therapeutic interventions such as transfusion, infusion of inotropic drugs, and infusion of vasoactive drugs or altering heart rate[2].

Existing methods of measuring cardiac output are unsatisfactory for various reasons. If carefully carried out, the Fick method is accurate but requires a pulmonary artery catheter that is not practical in routine clinical practice. Several variants of this method have been devised, but their accuracy leaves something to be desired. Transoesophageal echocardiography (TOE) provides diagnosis and monitoring of a variety of structural and functional abnormalities of the heart. It can also be used to derive cardiac output from measurement of blood flow velocity by recording the Doppler shift of ultrasound reflected from the red blood cells. However, reviews of this method have been mixed. The main disadvantages of this method are that a skilled operator is needed to utilize it, the probe is large and therefore heavy sedation or anesthesia is needed, the equipment is very expensive, and the probe cannot be fixed so as to give continuous cardiac output readings without an expert user being present[2].

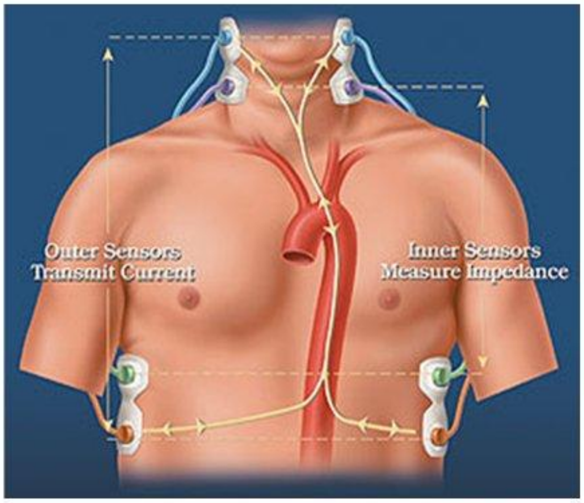

Figure 1: Current Impedance Cardiography electrode placement.

A final existing option that holds promise is impedance cardiography, first described by Nyoer in 1940[3]. The conventional impedance cardiogram is a record of variations of chest impedance (resistance to current flow), obtained by using an electric current passed in the head to foot axis from the neck to the upper abdomen as seen in Figure 1[2]. This high frequency, non-stimulating current is not only noninvasive, but painless to the patient as well. The frequency of the current (about 100 kHz) passing through the chest and heart is high enough to prevent sensation or muscle stimulation but low enough so that the pattern of current flow is similar to that of direct current[4].

Traditionally, chest impedance is recorded between the thoracic inlet at the base of the neck and the thoracic outlet at the level of the diaphragm. The impedance signal is related to changes in the size and composition of blood-containing structures within the chest, and it is by this reasoning the impedance cardiogram promises to reveal meaningful information concerning cardiac output and the effectiveness of the heart as a pump on a beat-by-beat basis. This would be extremely useful for monitoring critically ill patients and patients undergoing anesthesia, especially in cases where blood volume or cardiac output may change significantly[1].

Although indices derived from the chest impedance signal track cardiac stroke volume very well, the absolute values of stroke volume in units of milliliters of blood per heartbeat have been considered unreliable. This is especially the case in a situation involving congestive heart failure when the ventricular ejection fraction is greatly diminished, or in patients with either reduced or increased peripheral vascular resistance[3]. In addition, comparisons of impedance based stroke volume and cardiac output with results from the green dye dilution or the Fick methods show that the impedance cardiogram tends to overestimate stroke volume by 5 to 10 percent, with rather wide standard deviations, leading to the conclusion that the impedance method is not accurate. Recent studies have emphasized that changes in the impedance of lungs, great vessels, cardiac atria, and cardiac ventricles during the cardiac cycle are complex and countervailing, leading to a small net signal of uncertain origin. In sick patients with varying pathophysiology, such as reduced ventricular ejection fraction or reduced peripheral vascular, the factors that combine to give reasonable predictions in more healthy individuals may fail[2]. Accordingly, interpretations of impedance cardiographic data have tended to be tentative and guarded, and acceptance of the technique is not widespread and has not been able to replace traditional invasive methods. However, progress can be made by looking at impedance cardiography from a new perspective and considering an electrode arrangement that forces current through the cardiac ventricles, i.e. electrodes placed directly over the heart instead of the neck and abdomen. Anatomic and physiologic modeling of this approach lead to several surprising results, and indicate that impedance based methods can provide accurate, painless, and noninvasive cardiac monitoring on a beat-by-beat basis[4].

The purpose of our group project is to design a spatially specific 100 kHz system with four reusable electrodes placed over and close to the heart as well as a mechanical method for applying the electrodes at various spacing. The final prototype will be used for research purposes in improving the cardiography technique and will eventually be used in a medical setting.

III. Client Specifications:

Requirements specified by our client for the design center around placement, ease of use, and patient comfort. The model should permit proper placement of the electrodes directly over the heart, and as ventricle placement differs among people the model must allow adjustment and modification of electrode positions. The device must also be easy to place onto the patient, and repositioning of electrodes must also be simple and straightforward. In addition, the process of securing the device onto the patient should also be timely, requiring no more than fifteen minutes. Lastly, the device should be relatively comfortable for the patient, and allow impedance measurements to be taken throughout various patient positions (standing, sitting, walking, etc.). This also means that the device must be secure; that a patient is free to move without risk of the electrodes being repositioned or detached. Also, the client specified that the device and the electrodes themselves should be reusable, as opposed to current system of one time use electrodes.

IV. Designs

i. Design: Electrode Track

One way of fulfilling the requirement of having stable but movable electrodes is to have them contained within a track design. This design utilizes a tough but slightly flexible piece of rubber that can curve to a person’s body, but give the required support to hold four electrodes. This design employs two pieces of rubber as can be seen vertically in Figure 2. The inside portion, a horizontal projection from the two vertical pieces in the picture, would have holes running along the sides allowing for placement of the electrodes, or the track design. The encased electrodes will have a hard plastic outside so that nails or some locking pin can be placed through the electrode and the holes in the rubber. Four or five cross connecting sections will ensure that the pieces of rubber will not separate, yet be small enough not to hinder the electrode placement. The hard plastic part of the electrode will extend across the open expanse, and have a hole in the middle to

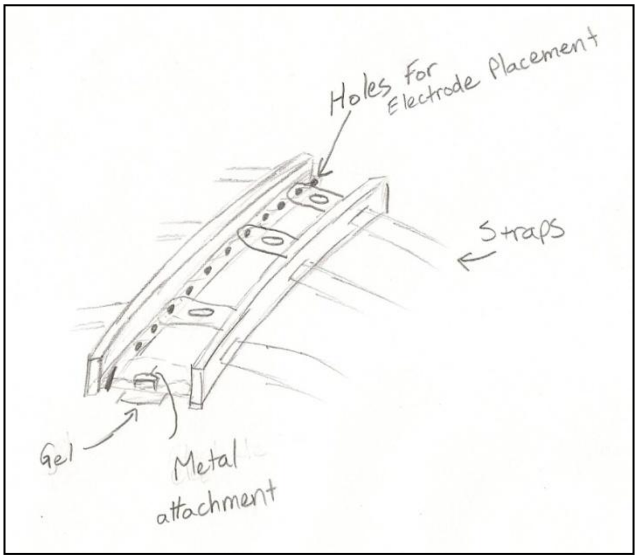

Figure 2: Electrode-Track design scheme

allow the electrode to be connected to the wires. The more flexible part of a traditional electrode will be under the hard rubber part and will have the required gel to sufficiently transfer the current to the body. The two large rubber pieces will have three connections for straps to go around the body to allow us to turn the collective track design in a linear direction of the best possible signal. This design offers a tremendous amount of durability and reusability. The rubber and plastic will not break down over time as much as silicone gel or mesh. Possible problems with the design are stability of the system as a whole. The only safe non-invasive connection to the body is through two-sided tape on the rubber pieces that touch the skin. In addition, this little amount of connection to the skin does not bode well as the person begins to move around. The biggest problem with this design is the bulkiness and weight. The rubber track design will not be able to stay in its desired location very well while the patient moves. Patient discomfort during movement is likely while wearing this because of its weight and bulkiness.

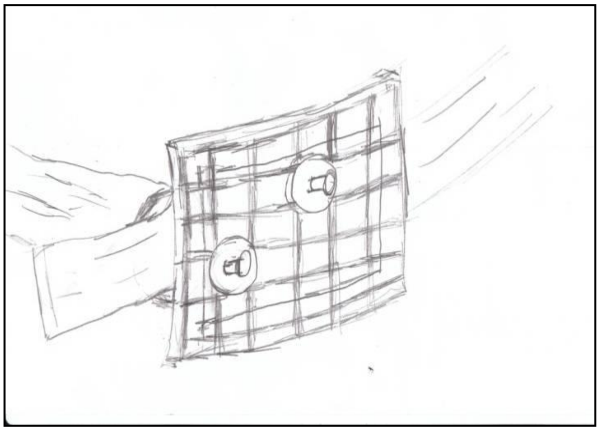

Figure 3: Basic schematic of Mesh-Liner electrode holding system

ii. Design: Mesh-Liner System

The mesh fabric design focus centers on comfort and the ease of adjustability. The fabric holding the electrodes taking impedance readings is made of a porous mesh, making it both flexible and breathable. The electrodes can then be wedged into the holes of the mesh, securing them in place. If the electrodes need to be adjusted in order to obtain a better reading, they can be quickly removed and placed onto any hole in the fabric. The fabric piece is then lined with a shelf lining material to provide extra grip when in contact with the skin. This prevents the electrodes from sliding out of place during a test. Finally, the fabric is strapped to the body with an elastic band wrapped around the chest, preventing the user from feeling constricted. This band would be attached to one end of the fabric, wrap around the back of the user, and circle through a ring attached to the other end of the fabric. The free end would then Velcro to the encircling strap, allowing for it to be easily adjusted once in place without obstructing the mesh.

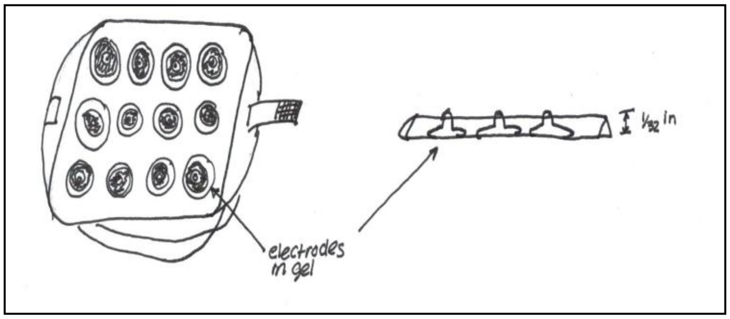

Figure 4: Gel electrode matrix schematic

iii. Design: Gel Electrode Matrix

The next possible design that was considered as a viable alternative to the current impedance electrode system was a gel electrode matrix. Here, a certain number of electrodes would be suspended in silicone rubber compost, forming a matrix of electrodes. Also, there will be a plastic of harder density located on the surrounding edges of the matrix as seen in Figure 4. This is done so as to provide the silicone rubber gel matrix with support, ensuring it won’t tear when loaded with force. An elastic strap is then attached on one end of the matrix and then threaded through the other end. This elastic strap, as mentioned in previous designs, will secure the matrix tightly to the body, allowing for only minute electrode movement. This is an imperative aspect of the design; movement of the electrodes results in a less accurate cardiac output readout. This design is by far the easiest to use. Instead of vastly focusing on placing the electrodes in the proper area, and moving them if they do not give the best reading, the matrix can allow for a variety of spatial combinations and signal readouts to be attained with little or no hassle. However, there is one drawback to this design: the amount of conductive electrode gel needed. As commonly known, electrodes must be gelled in order to provide a conductive contact with the skin for ease of signal travel. Thus the entire matrix must be gelled; this will be quite messy and tedious for those using this design. However, overall this design is by far the easiest to use while maintaining a proper electrode-skin contact ratio.

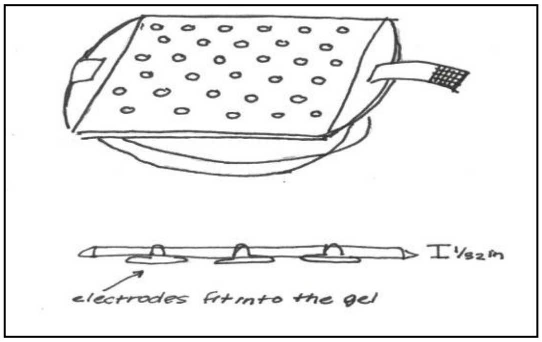

Figure 5: Gel liner system diagram

iv. Design: Gel Liner System

The final design pathway that was analyzed and considered was the possibility of using a gel liner system. Here, a silicone gel rubber will be used to help secure electrodes. This will be done by placing several holes of the proper diameter in this gel, making it somewhat mesh-like as seen in Figure 5. With these holes, electrodes will be able to be placed anywhere through the gel mat allowing for an adjustable system. Surrounding the edges of this gel mesh is a harder PVC plastic. This allows for an elastic strap to be attached to the system, firmly securing the electrodes to the body. With the use of the harder plastic on the edges, the deformation of the gel matrix will be slight and the possibility for ripping in the silicone gel will diminish. With this system in its entirety, gel electrodes will have to be placed on the body, then attached to the gel mesh, and then hooked up to the impedance monitor. This could be tedious work for a nurse or doctor performing the test. However, this gel pad will firmly conform to the body and provide great electrode placement stability, reducing electrode movement.

V. Final Design

In order to help determine which final design was the most efficient and plausible to pursue, the design matrix below was used. Each of the four designs was evaluated over five design considerations. These included, as seen above, ease of use and electrode placement stability, as well as the comfort, size and reusability of the design. For the ease of use category, each design was evaluated how easily it could be set up and properly perform for the user. Next, for the placement stability category, each design was evaluated as to how well it maintained a constant electrode placement, providing little or no movement of the electrodes themselves, as well as how great of an electrode-skin contact would be sustained. Lastly, for the reusability category, each design was evaluated as to how long it would last as well as how it worked with reusable electrodes. These three categories that were just discussed were weighted twice as much as the other

	Ease of Use (20)	Placement Stability (20)	Comfort (10)	Reusability (20)	Size (10)	Total (80)
Plastic Track System	8	5	2	7	7	29
Gel Electrode Matrix	18	16	8	20	9	71
Gel Liner System	18	18	8	20	9	73
Mesh & Liner System	19	16	9	18	9	71

categories involved due to the fact that they identify the important specifications of the client. When each design was evaluated on the basis of a one hundred point system it was determined that the most effective design is the Gel Liner System. This is in fact the final design that was selected to pursue. In review, the final design contains a silicone rubber supported by hard plastic edges, and held on the body via an elastic strap.

VI. Final Design Construction

The final design was constructed using a basis found in both the previous gel matrix and gel electrode matrix design. First, as seen in the earlier final design concept, the base of this electrode system is made up of a silicone rubber equivalent to that used in a "Wilton Silicone Baking Mat". This material is smooth, easily conforming to the natural curves present in the body. On opposite ends of the square base, there are slits approximately 2 inches in length. These slits serve the purpose of allowing a securing strap to hold the system firmly against the body. Due to the material property of silicone to rip easily as well as hindering the ease of adjustment by way of the elastic strap, there was a need to revise and reinforce slits. First, slits were cut in a fold of nylon plastic with accordance to those present in the base. The folds of nylon plastic were then placed on the edges taking note that the slits were superimposed on one another. Once this was done, the inside edges of the nylon slits were lined with electrical tape, which ensured the elastic strap to slide easily back and forth. The silicone base also withholds modified electrodes which are imbedded through it. Looking at the image

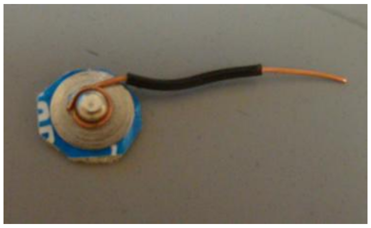

Figure 6: Modified electrode

above, the detail of the modified electrodes can be seen. The electrode base was trimmed down dramatically leaving only a circular section containing the electrode lead itself along with the conductive, absorbent foam present on the bottom. When placing regular electrode leads into holes cut in the silicone base, it was determined that the connecting alligator clips were unable to grasp the small amount of electrode peaking through the holes. Thus, it was come to the conclusion that the electrode leads needed to be lengthened somehow. This was accomplished wrapping a conductive wire around the electrode base and then soldering that wire to itself, considering the stainless steel electrode leads do not cooperate with the soldering process. Once this was done, the wire was threaded through pre-cut holes in the base and then knotted in order to ensure a minimum movement of the electrodes. Lastly, lining the inner side of the electrode holding system is a hydrophobic mesh material. This was done to guarantee the electrode gel did not stray from one electrode to the other and thus muddle with the output signal by creating a short circuit. All these encompassing features can be seen when viewing the images below.

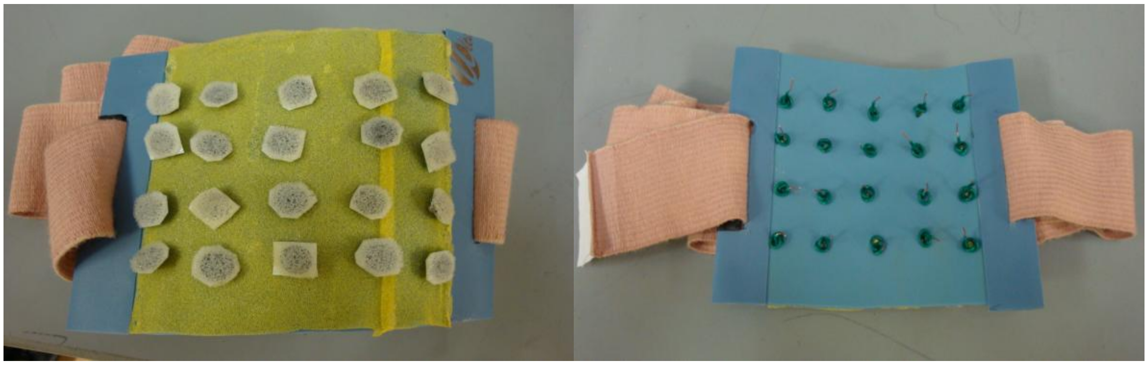

Figure 7: Final design prototype detail

VII. Materials and Methods

For the final design, one of the first things purchased was a pliable silicone mat that would serve as the support for the electrode matrix. Flexible, nonconductive and resistant to excessive stretch, it was a suitable choice and was cut to approximately 4’’ by 6’’ dimensions. Twenty Monitrode electrodes were positioned within twenty holes that had been punched through the silicone, and copper wire was carefully wrapped around the electrodes, soldered and knotted to provide for easy attachment of the alligator clips. After cutting slits on either side of the silicone matrix to allow the fastening of the elastic band that had also been purchased, it was discovered that pulling the bandage would quickly lead to tears in the silicone. Thus a firm plastic sheet, acquired from a student folder, was cut and super glued around the slotted ends provide extra support and resistance to tearing. Also, to prevent the spreading of electrode gel, which would interfere with the signal, a hydrophobic mesh was glued to the bottom of the matrix. Although not used in the electrode matrix prototype, in order to conduct testing, two TLO82 Dual BiFET OP Amps as well as two circuit breadboards were purchased in order to build the circuit components necessary for testing. The resistors, capacitors, and remaining circuit components were provided to us through the Engineering Centers Building’s bioinstrumentation lab. A full cost analysis of our materials used follows:

Wilton Silicone Baking Mat, 12’’x17’’	($5.97)
ACE Standard Self Adhering Bandage	($6.49)
Twenty Monitrode Electrodes	(provided by client)
Mueller Sportcare Multipurpose M Wrap	($3.59)
TLO82 Dual BiFET OP Amps	($10.00)

- Two circuit breadboards ($10.00)
- Resistors, capacitors, and remaining circuit components (provided through the Engineering Centers Building's bioinstrumentation lab)

VIII. Testing and Results

i. Prototype Testing

In order to determine if the constructed prototype was a viable alternative to current impedance gathering methods it was tested on a live human subject and then compared to two other methods of impedance cardiography. In every test performed, the electrodes were sufficiently covered with a semi conductive electrode gel and then hooked up to the amplifier in accordance with the proper procedure. First, as seen in Figure 8, the first technique of impedance testing performed utilized the traditional method.

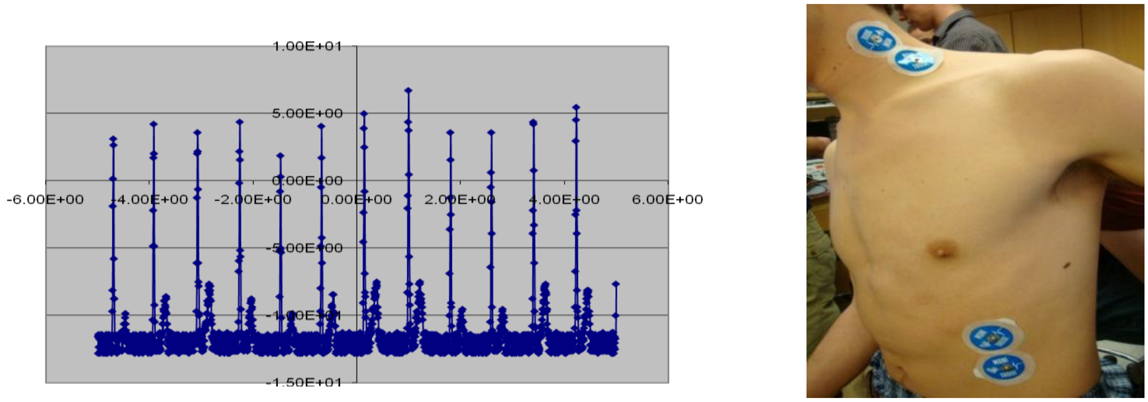

Figure 8: Traditional impedance method test and output signal

Looking to Figure 8, the traditional method of impedance cardiography utilizes four electrodes, two placed between the neck and the shoulder and two placed at the heart. This produced a rather strange output signal. As seen, there is an apparent EKG spike however; there is only half of the signal appearing. The only reason that can possibly explain this state of affairs is the peculiarity in electrode placement. It is reasonable to assume that because the electrodes are so far from the heart it causes the output signal to be greatly affected.

The next technique of impedance testing utilized the centered electrode method.

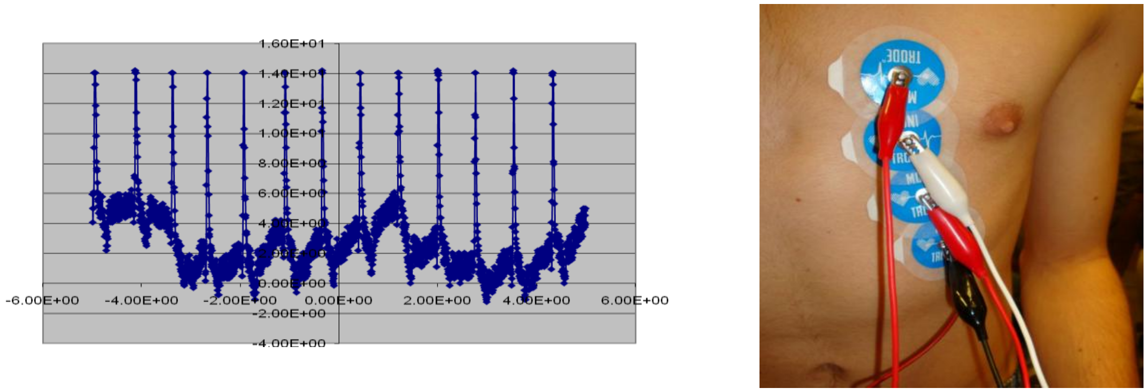

Figure 9: Centered electrode method test and signal

Looking to Figure 9 above, the centered electrode method employs placing four electrodes in a line directly over the location of the heart. This method generated a normal, clear output signal where the EKG and clear PQRS heart wave were presented ever visibly. In this instance, because the electrodes were both close to one another and placed in the direct location of the heart there was no obstruction that would have resulted in a muddled output signal. The centered electrode method requires a basis to compare all other output signals considering the fact that there were no apparent obstructions with either the circuit or attaining the signal. This method can be depicted as the control impedance cardiography test. There were no present variable and thus there exists no variation within the data attained.

The last technique of impedance testing was performed utilizing the constructed prototype. Here a random set of four electrodes were chosen and hooked up to the amplifying circuit. As seen in Figure 10 the matrix electrodes are placed closely together and in an optimal location relative to the heart.

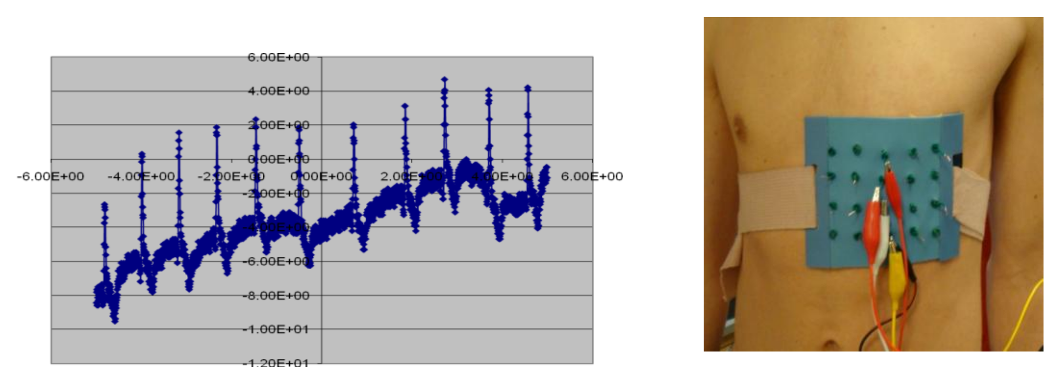

Figure 10: Prototype test and output signal

An output signal was generated that is significantly similar to the signal attained during the control centered electrode test. Again there is a clear ECG and PQRST heart wave present within the signal. Consequently, it would be reasonable to assume that the prototype electrode holding system provides a viable alternative method to attain readings from an impedance cardiography test.

ii. Comparison

One of the ultimate goals of this project was to prove that the repositioning the electrodes closer to the heart would generate a more accurate signal with better resolution than the traditional method. Looking at the graph produced using the prototype and the graph produced by placing four generic electrodes over the heart, these two techniques produced far better results than the traditional test for impedance cardiography, which has electrode placement on the neck and the abdomen. In the two previous tests, a very good signal was seen with a full EKG and a very probable pressure wave that is slightly hidden in the noise of the amplifier as well as the EKG signal. Looking at the graph using the traditional electrode placement to measure impedance there is no pressure wave and the data is not very useful. The EKG still exists, but the desired data is not attainable through these methods. In the final meeting of the semester with Professor Webster, he made it clear that being able to prove that our not only our prototype but having evidence that electrode placement closer heart is the only true way to be able to conduct impedance cardiography. The traditional method of impedance cardiography just is not capable of accurately measuring the resistance of the blood as it leaves the heart because the current is traveling through more of the body. The last test confirms this belief and proves that the prototype can produce a better signal and once it is possible to isolate the pressure wave from the heart and remove the EKG from the signal, we should be able to determine the velocity and volume of blood running through the aorta.

IX. Ethical Considerations

The first and foremost ethical consideration regarding this project is personal safety; the prototype and final product must be safe enough to both handle and use on human subjects. In this case, the primary concern is electrical safety. The product must be securely insulated and must be able to safely apply electricity to the body without creating the potential for serious harm. In other words, all aspects of the design, including the amplifier and electrode holder, must be able to safely handle the electrical lode applied to it without failing or overloading.

In order to address this issue, the amplifier’s bias current was tested to make sure the current running through it is safe to apply to humans. The measured bias current was 11.29 nA, much less than the standard 10 uA maximum threshold for safe level of current. As a result, the amplifier meets safety standards and is safe to use on human subjects.

X. Conclusion and Future Work

The success in proving that the prototype has more potential than traditional impedance cardiography will allow us to move ahead, fix some technical difficulties, and look at some ways to improve the prototype and make it exceptional. The biggest challenge is to remove the EKG from the signal and reduce the noise during signal amplification by debugging our amplifier. There is also a need to build a better mechanism for the attachment of alligator clips to the prototype, as well as an improved system of prototype attachment to the body. In addition, determining the best placement above the heart is paramount to finding a signal with less noise and maximum intensity.

One possible way of improving the signal and reducing noise from the prototype is to build a device to support the alligator clips on the prototype rather than the current technique. Currently, the alligator clips are attached directly onto the electrodes of the device; this pulls the prototype away from the body, impairing electrode contact with the skin and decreasing the signal. Initial ideas to combat this problem include routing the alligator clips through some holes positioned on top of the device, so the stress is placed more on top of our prototype thus pushing it down into the skin more. Another idea is to wire the electrodes to a plate on the prototype for easier attachment.

In addition, a better way of attachment to the skin must be found that will be easier for possible clinical applications. The current method of using a strap is effective for current testing but practically having a reusable electrode prototype will only add to its bulkiness because of the need to wash the device after each use. This is not very attractive to the medical community not only because of possible disease implications, but also it is cheaper to have a device that is used once then thrown away rather than hiring someone to sanitize this device after each use. A possible way to improve the prototype for future use is to use an adhesive on the edges or in between the individual electrodes rather than a strap. Having an adhesive in between each of the electrodes will add to the electrode contact and contain the gel required for the passing current, this will improve the signal and increase overall effectiveness.

As testing continues, it is paramount that research is performed to determine the best possible electrode positioning for maximum signal. In the first meeting with Professor Webster, he stressed the need to find the point of maximum signal over the heart so that we can efficiently use our device. In the future, it must be possible to determine which of the electrodes on the prototype will be most successful during testing. As this point will change with every person, the requirement to fulfill this goal will be to research the use of ultrasound to find the point of maximum intensity.

Shortly before the end of the semester, a high-pass filter was built in order to remove the EKG and isolate the desired pressure wave. This attempt was able to remove the EKG largely through the first part of the three filter's we built, but as we moved into the second and third the entire signal was also removed. In the future, building a phase sensitive demodulator will allow removal of the EKG from the data and isolate the pressure wave, as well as reduce the overall noise of the system. The phase sensitive demodulator is the focus for future work, because the main goal of the entire project is to use the signal achieved through our prototype to accurately measure impedance cardiography. One other possibility that was brought up during the poster session presentation would be to use LabView; unfortunately, because of our relative inexperience with LabView, we have not learned how to effectively use this program. In conclusion, throughout a semester of working on improving impedance cardiography, we were successful in proving that electrode placement closer to the heart gives a better signal to work with. In the future, we will attempt to properly isolate our desired pressure wave so has to begin measuring blood volume being pumped out of the heart.

XI. Appendices

i. References

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ii. Product Design Specifications

Function:
Current methods for measuring cardiac output are invasive. A noninvasive method is impedance cardiography, which measures cardiac output by running a current through the heart ventricles via 4 electrodes and monitoring the measured resistance. As it stands, the accuracy of this method is poor because the electrodes are far away from the heart and thus it is more difficult to distinguish between actual signal and noise. Our client would like us to design a spatially specific 100 kHz system with electrodes over and close to the heart and

design a mechanical method for applying the 4 reusable electrodes at varying spacing over the heart.

Client Requirements:

- 4 reusable electrodes
- Method of determining ventricle location in live patients
- System of holding electrode device to body
- 100 kHz current system

Design Requirements:

1. *Physical and Operational Characteristics*

- Performance Requirements: Reusable electrodes (for multiple patients). Electrodes must have some way to conduct electricity. Suitable for a wide variety of patients (different sizes, gender, etc.)
- Safety: Must not put patient in danger of electric shock; must keep frequency above 100 kHz. Should have instructional manual and safety warnings for those operating device.
- Accuracy and Reliability: In the long run, impedance cardiography machine should be as accurate as the current invasive catheter method currently used in hospitals to measure cardiac output.
- Life in Service: Should be able to become a long term fixture in hospital and lab settings, i.e. Length of life in service should be measured in years. Electrode brace and electrodes should be used on tens, probably hundreds of patients.
- Shelf Life: Must withstand operating room conditions and should be built to last. Certain parts, particularly the electrodes, should be constructed to be reusable in order to increase the lifespan of the device.
- Operating Environment: Impedance device should be used in either a lab or medical setting.
- Ergonomics: The device must limit itself to 100 kHz
- Size: The electrode brace should be small enough to maneuver be placed easily on the body and lay within a close distance from the heart, but large enough to accommodate the 4 electrodes.
- Weight: The electrode brace should be light enough to be able to be worn comfortably while the patient is standing.
- Materials: The electrode brace must be made of nonconductive materials, so as not to distort the signal generated by the heart.
- Aesthetics, Appearance, and Finish: These are not of primary concern, but the device should not scare the patient.

2. *Product Characteristics:*

- Quantity: One testing unit is necessary.
- Target Product Cost: This has not been determined.

3. *Miscellaneous:*

- Standards: Once an appropriate design is achieved, human testing must be implemented to determine the safety and accuracy of the device.

- Customer: Accurate, mobile (able to move from room to room), should be any more expensive than current method.
- Patient Related Concerns: Electrode brace should not be cold and hard and the patient should be able to stand comfortably.
- Competition: Yes, the main competition is the current invasive catheter method, which has proven accuracy and is already being used in most hospital settings.