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. 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. 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. 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, infusion of vasoactive drugs or altering heart rate.

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 the basic method have been devised, but their accuracy leave 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.

A final existing option that holds promise is impedance cardiography, first described by Nyoer in 1940. 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. 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

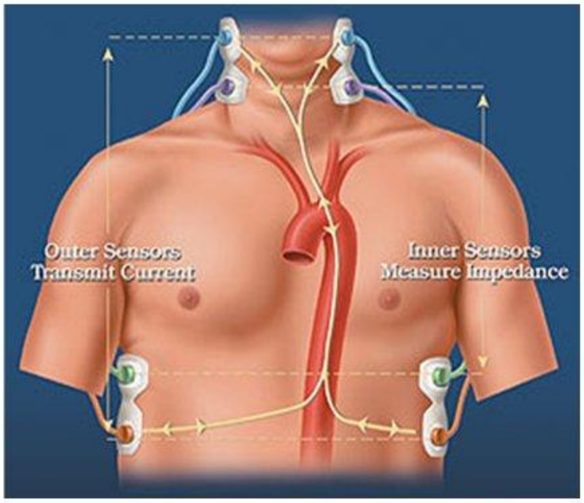


Figure 1: Current Impedance Cardiography electrode placement.

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.

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.

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. 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. 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.

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.

III. Client Specifications:

Requirements specified by our client for our 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, our 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 our requirements to have 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 you can see 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

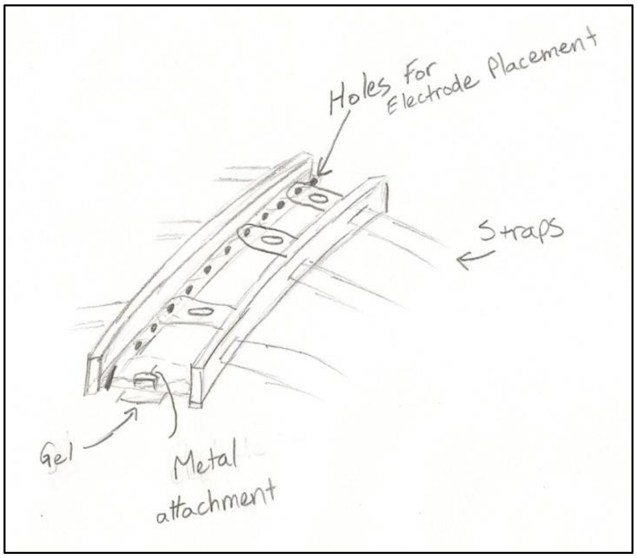


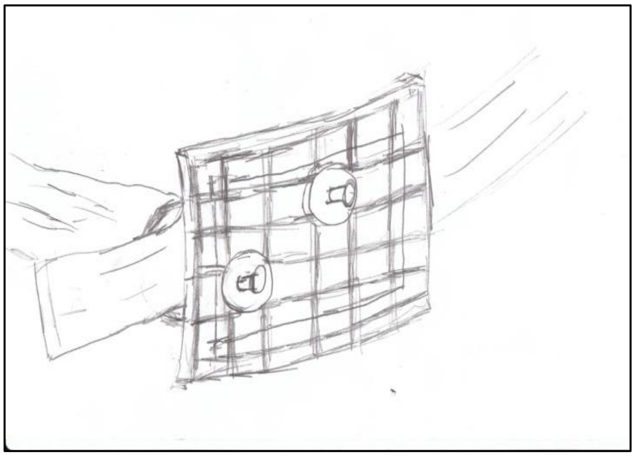
Figure 2-Electrode-Track design scheme

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 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.

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 3-Basic schematic of Mesh-Liner electrode holding system



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

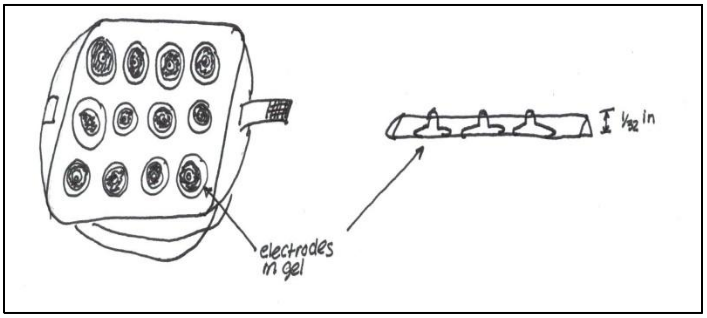


Figure 4: Gel electrode matrix schematic

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 doesn’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.

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,

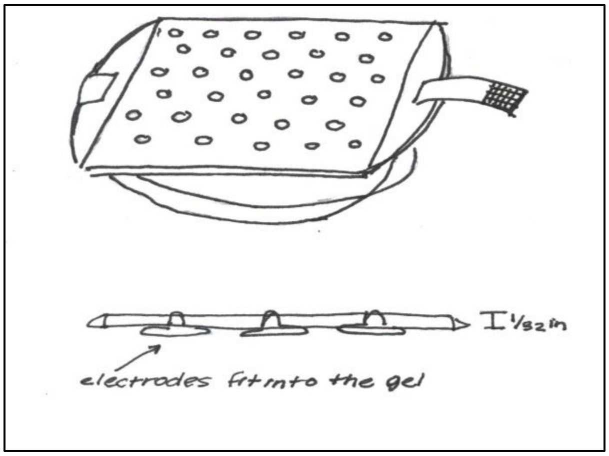


Figure 5: Gel liner system diagram

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. Materials

The remaining designs use a range of materials for the electrode vessel including plastic, mesh fabric, shelf liner, and silicone rubber gel. These materials and their properties weigh heavily in the design matrix, as they are some of the largest contributing factors to each category. Each of these materials was initially chosen based on its poor conductance, so as to reduce errors in measurements and capacitance problems that may otherwise occur. While this is true for each of the materials, their unique properties offer some advantages while others prove to be disadvantageous. For example, plastic is flexible, easy to maintain, and durable, but would be uncomfortable for the user. Mesh fabric, on the other hand, would be breathable, flexible, and soft, but would also require more time to wash than would plastic and is more apt to losing its structure over time. Also, shelf liner is a great material for providing extra grip due to its increased surface area and rubber nature, but would also collect dirt easily and is more difficult to clean. Similarly, gel is flexible, soft, and holds its shape well, but would require effort to keep clean. Even so, the flexibility and durability of gel makes it the best material to use to hold the electrodes.

VI. 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

	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

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 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 has been selected to pursue. In review, the final design will contain a silicone rubber gel mesh that is supported by hard plastic edges, and held on the body via an elastic strap.

VII. Future Work

The biggest part of the project still lies ahead in building and testing our possible design. Before we can build our initial prototype, we will have to look into our materials and decide if they are cost effective or even possible. Once we have a final answer on materials, then we can move ahead and choose the best possible design after we eliminate any designs that are not plausible. We will have to build at least two different prototypes to ensure that we offer the best possible solution to our problem. We will test each prototype to determine if it can produce a more accurate and reliable signal than the current methods. If we are able to produce more accurate and reliable signals then we need to determine which design gives the best signal, which design can hold up over time the longest, which is the most comfortable to the user, which offers the user to have the most freedom to move around, and which is the most cost effective. Once we have chosen our best possible prototype we will build a final prototype to be presented to our client, professors and fellow students.

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