Impedance Cardiography

Client: Professor Webster
Advisor: Mr. Dennis Bahr

Leader: Jacob Meyer
Communicator: David Schreier
BSAC: Tian Zhao
BWIG: Ross Comer

Table of Contents

I. Problem Statement

Current methods for measuring cardiac output are invasive. Impedance Cardiography is a non-invasive medical procedure utilized in order to properly analyze and depict the flow of blood through the body. With this technique, 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, our client hypothesizes that the current method withholds degrees of inaccuracy due to the mere fact that the electrodes are placed too far from the heart. The goal of this project is to design an accurate, reusable, spatially specific system that ensures more accurate and reliable cardiographic readings. Furthermore, this system must produce consistent results able to be accurately interpreted by industry professionals. More specifically, our primary goal is to ensure the device must not only collect an impedance signal, it must also isolate the signal in its output using a variety of filters

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 normality such as sepsis or cardiomyopathy then a 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 impedance cardiography can be used [3]. Impedance cardiography is used to the change in resistance of the aorta has blood passes through [2]. These changes in resistance can then be used in specific equations to calculate the pressure and flow blood out of the heart, this in turn can then be used to calculate cardiac output [1]. These 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 [4].

Existing methods of measuring cardiac output accurately are very invasive and because of this, these procedures are rarely used, despite the obvious benefit. 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, and the accuracy of invasive measures is unmatched thus far in impedance cardiography [4]. Transoesophageal echocardiography (TOE) provides diagnosis and monitoring of a variety of structural and functional abnormalities of the heart [3]. This process can be used to derive cardiac output from measurement of blood flow velocity by recording the Doppler shift of ultrasound waves reflected from the red blood cells [3]. The main disadvantage of this method is that a skilled operator is required to perform surgery. The probe is large and precision is required, as well as anesthesia on the patient which just drives up the cost of the operation. The equipment is very expensive, and the probe cannot be fixed to give continuous pressure and flow readings without an expert surgeon.

A non-invasive option that could potentially save money for the patient and increase ease of measuring cardiac output is impedance cardiography, first described by Nyoer in 1940. The conventional impedance cardiogram is a record of variations of chest

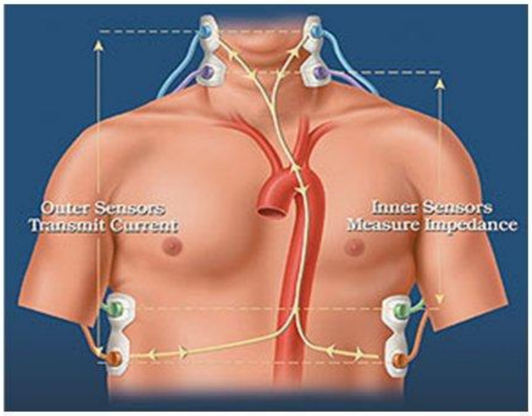

Figure 1: Current Impedance Cardiography electrode placement.

impedance (resistance to current flow), obtained by using an electric current passed from the neck to the upper abdomen as seen in Figure 1 [1]. This high frequency, non-stimulating current is not only noninvasive, but painless to the patient as well. The frequency of the current (about 150 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 [1]. 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 [4]. 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 [4]. 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 of blood per heartbeat are considered unreliable in most clinical settings [4]. 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 [4]. 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 cardiography method is not accurate [3]. 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 [4]. 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 the data from impedance cardiography 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.

Despite these limitations, taking a new perspective on electrode arrangement that would force current through the cardiac ventricles [5]. By placing the electrodes directly over the heart instead of the neck and abdomen, it is proposed by Professor John Webster that we can attain a more accurate signal. 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 of cardiac output continuously during the entire cardiac cycle [5].

The goal of this project is to design an accurate, reusable, spatially specific system that ensures more accurate and reliable cardiographic readings. Furthermore, this system must produce consistent results able to be accurately interpreted by industry professionals. More specifically, our primary goal is to ensure the device must not only collect an impedance signal, it must also isolate the signal in its output using a variety of filters. During the previous semester the impedance cardiography group was able to develop a spatially specific electrode array for use in testing of the proposed new electrode positions by professor Webster. While the group was able to attain some promising data of relative changes in resistance per heart beat, the ECG signal was a huge interference on top of the changing resistance. In order to fix this problem, this semester our new impedance cardiography group is designing two filters, a passive filter system and possibly a phase sensitive demodulator designed by our international colleagues from China. The final prototype will be used for research purposes in improving the cardiography technique and will eventually be used in a medical setting.

III. Global collaboration

UW-Madison is promoting an international exchange program with China to expand UW BME program outside of the boarder. Gladly, two more Chinese students join in our Cardiograph Impedance team and they will be advising and participating in the design process. It is a very encouraging step to take, since UW Madison is the one of the pioneer institutions that experiments in the area of international engineering education. It is also a valuable design experience, because we get extra helps and perspectives from students in another country.

The two international colleagues are Bi-chao Chen and Yu Chan. They come from Zhejiang University, Zhukezhen Biomedical Engineering Department, which is a prestigious institution with strong science research background worldwide. Both of them are seniors with electrical engineering background. They will be advising, and also participating in designing a signal demodulator for the Cardiograph Impedance project.

IV. Client Specifications

The requirements specified by our client cover a range of topics, including placement, ease of use, patient comfort, and output. Our main task, however, is to focus on electrode placement and signal output. Our device must place four electrodes directly over the heart as opposed to placing them on the neck and abdomen as current methods do. This in turn means the best positioning of the electrodes must be determined in order to obtain the clearest signal with least interference from the heart's electrical signals. Similarly, our amplifier circuit must also eliminate EKG interference by means of electrical filtration. The amplifier portion of the cardiography system should be designed to reduce electrical noise from the heart and only let through the impedance signal we wish to obtain and analyze. We have in turn proposed three circuit designs to accomplish this task.

V. Designs

1. Design: Amplifier Only

Every time the heart beats it emits an electrical signal that can be detected on the surface of the skin. However, this signal is often very weak and can contain unwanted noise or electromagnetic interference (EMI) [6]. The amplifier we built for our project is an ECG amplifier that amplifies the signals from the heart. The amp is connected to two electrodes located over the aorta of the heart. The amplifier sends signals from the heart to the oscilloscope, illustrating the blood pumping from the heart. This amplifier is a necessity for our project to work and it is crucial that our amplifier is precise [7]. However, the amplifier by itself isn't able to eliminate the EKG signals from the graph we need to look at to quantify the blood pressure in the aorta. Our goal, as mentioned before, is to filter out the undesired frequencies outside the passband of .5 to 20 Hertz. In order to do this we need some sort of filter.

2. Design: Demodulator

Demodulation can work in a variety of situations. For instance, individual telephone signals are modulated with radio waves in order to travel in long distance. The telephone signals riding on top of the radio wave, which is the carrier wave in this case, must be demodulated before it is ready for final analysis. Demodulation is a process that eliminates the carrier wave and extracts the signal envelop.

For our demodulator, the demodulator is designed to eliminate the 150kHz signal, which we used as an original source that is sent through the aorta of subjects. The demodulator will extract the signal envelop, which possibly indicates cardiac output. The modulated signal should have lower frequency than the carrier signal. We expect this to be within the rage from 0.5Hz to 20Hz.

The advantage of this design is that it is very convenient to use. The demodulator is the only design we need in order to filtrate the 150kHz carrier frequency. It is relatively simple regarding its ease of uses and manufacture. However, the extracted signal could contain much noise, which is possibly caused by muscle contractions and physical movements. It is therefore hard to tell whether the envelop contains valuable information or simply irrelevant noises. One possible improvement is to add filters with the demodulator to eliminate interferences.

Bi-Chao Chen proposed a demodulator he designed himself. The following is his description of the design he constructed:

Function:

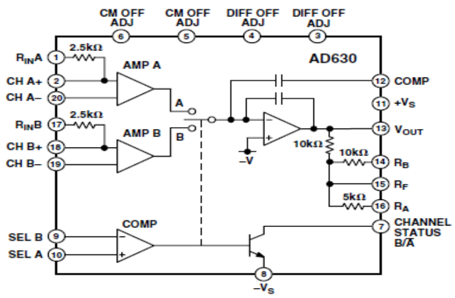

Figure 2: Functional Block Diagram

The demodulator is based on AD630. There are two input channels on the chip, Channel A generates an inverting gain and Channel B generates a noninverting gain. The comparator is voltage sensitive and the circuit is switched between inverting and noninverting gain under the control of the comparator to an analog switch. With adequate connection we can receive modulated or demodulated output signal ground on the input signal that connected to the Channel A/B and the carrier signal which defines the frequency. The on-board resistors provides gains of ±1 and ±2, and we can change the gains by adding external structure. We design a balanced demodulator according to the information of AD630.

Architecture:

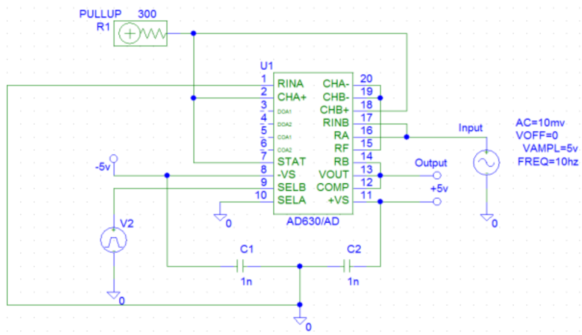

Figure 3: PSPICE Demodulator Architecture

The input is a sinusoid voltage signal generator connected Channel B; V2 is carrier wave connected to the comparator in order to control the analog switch; the pull-up resistor is used to denote a high level of the linked pins. AD630 provides common-mode adjustment and differential adjustment that we can add them into the demodulator to null the offset voltage so that the result will be more precise.

3. Design: Amplifier and Filters

Our third design for our project simply adds high and low-pass filters to the first design. These filters are able to eliminate the signals outside our desired passband. The low-pass filter decreases the gain in the higher frequency signals, reducing the gain in the high frequency signals over 20 Hz. The high-pass filters decrease the gain in the lower frequency signals, filtering out the signals under .5 Hz. Although it may not have the technical capacity of a demodulator, this design has already proven itself to successfully decrease the EKG signal when connected to a human subject (see figure 4).

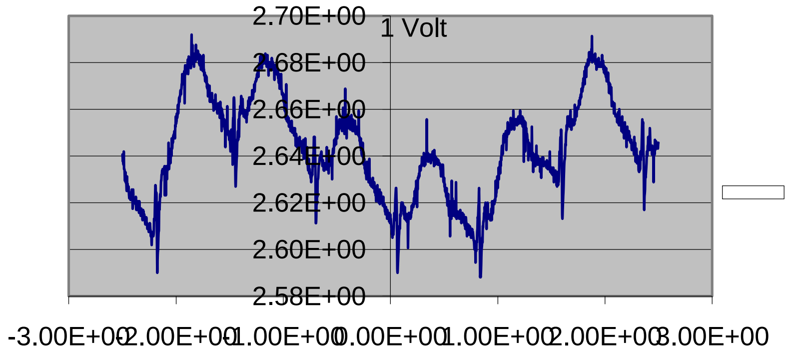

Figure 4: Impedance output from human heart using filter design

VI. Materials

The materials required for our designs consist primarily of standard circuit materials We needed three op-amps, many resistors, diodes, and filters, which were each provided to us. To build the first high-pass filter that comes before the amps, we used 1 nF capacitor and a 1k Ω resistor. We built this filter with the intention to remove the EKG signal. The build the second high-pass filter, which is used to offer a frame of reference for our signal, consists of a 3m Ω resistor and 1 nF capacitor. Finally, the low-pass filter we added to the ECG amplifier was constructed using a .7V diode, a .1nF capacitor, and a 1k Ω resistor. This low pass filter removes the 150kHz carrying signal.

VII. 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 three designs was evaluated over five design considerations. These criteria include ease of use, ease of manufacture, accuracy, size, and effectiveness. For the ease of use category, each device was evaluated based on how easy it would be to connect, maintain, or adjust if need be. Next, the designs were assessed based on how easy they would be to construct without risk of mistake. Each design was also evaluated on how accurate and trustworthy the signal yield would be, or how well the EKG would be filtered out. Furthermore, the designs were evaluated by size and how compact and easy to handle they would be, an important consideration for our confined environment. Finally, each design was assessed for its effectiveness. Although this category is more subjective, each design was rated based on its ratio between how easy it is to manufacture and operate versus the quality of results. After evaluating each system based on the eighty point system, the filtration design was determined to be the best design and the one that will be implemented henceforth. This system was chosen primarily because of the fact it has already delivered reliable data, and so is readily available, will not consume more time in construction, and is proven to be dependent.

VIII. Future Work

The remaining work to be done revolves around obtaining a clean impedance signal void of any EKG interference. This will be done first by establishing our filter design as a consistent method of data collection. This will require tests on human subjects in order to gather data that can be further analyzed. After initial testing, the filter system may have to be modified and adjusted until the optimal signal is achieved with least amount of noise. Once we have established a consistent reading from the amplifier and filters, we will have to determine the best position of the four electrodes to be placed over the heart to further reduce any noise. We will do this by using the electrode array apparatus we developed in the previous semester and sequential experiments. By comparing the results, we will be able to determine the positional of maximum impedance signal output and minimal EKG interference.

IX. Social 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.

References

[1] Mitchell, G. F. (2009). Clinical achievements of impedance analysis. *Medical & Biological Engineering &Computing, 47*(2), 153-163.

[2] O'Rourke, M. F. (1982). Vascular impedance in studies of arterial and cardiac function. *Physiological Reviews, 62*(2), 570-623.

[3] Sciences and Weldon School of Biomedical Engineering, Purdue University, West Lafayette Indiana. Submitted July 6, 2009.

[4] Van De Water, Joseph M, MD. Et al. "Impedance Cardiography: The Next Vital Sign Technology?". Chest. June 2003, vol. 123, pgs. 2028-2033.

[5] Webster, John; Bezrukova, Elena. Personal Interview. January 29, 2010.

[6] "Experiment 4: Sources of Biopotentials and Biopotential Amplifiers." *BE 3600 BIOMEDICAL INSTRUMENTATION (LAB)*. MTU.EDU. Web. 3 Mar. 2010. <http://www.biomed.mtu.edu/osoykan/classes/be3600/3600_lab/exp04.pdf>.

[7] Webster, John G., *Medical Instrumentation: Application and Design*. 3rd Ed. Philadelphia: W.B. Saunders Company, 1998.