Toward a Non-invasive Measurement of Cardiac Output

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by

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Background

Cardiac output is the volume of blood pumped by the heart into the aorta per unit time. It is the product of heart rate and stroke volume, that is, the number of heartbeats per minute and the volume of blood transported per beat. Cardiac output is an important physiological indicator of general health[i]. The circulatory system is responsible for delivering oxygen to every part of the human body, thus every organ system is dependent upon the circulatory system's operation.

While cardiac output varies with the amount of activity the body is engaged in, there are also particular trends in cardiac output useful for medical diagnostics[ii]. The performance of the circulatory system is often associated with the performance of other physiological systems in the human body. For instance sepsis, a bacterial infection of the bloodstream, is associated with elevated cardiac output[iii]. There is evidence that an early detection of this sepsis can increase the chances of successfully combating the infection.

Many medical complications are associated with premature infants, in particular, sepsis is a common problem for the prematurely born. Such infants, cared for in the Neonatal Intensive Care Units (NICUs) of hospitals, have great difficulty overcoming infections given that their bodies were not allowed to gestate for the full forty weeks that the average human infant has. NICUs monitor the vital signs of these infants, but the measurement of cardiac output presents a number of technical problems.

Many of the currently accepted techniques for the continuous measurement of cardiac output are highly invasive or expensive. Most require injections to be

made into the blood and then tracked. Others require inserting a pressure sensor into an artery and measuring the blood pressure continuously.

Chest impedance is often measured on premature infants in order to keep track of their respiration. Using electrodes that are put across the premature infant's chest, a small, high-frequency voltage is applied and the current is measured. The impedance varies depending on the impedance of the skin, muscles, and fluids inside the chest. While infants' respirations produce the largest impedance changes, the beating of the heart will also contribute to the chest impedance signal. It is this cardiac artifact signal that will be filtered and tested.
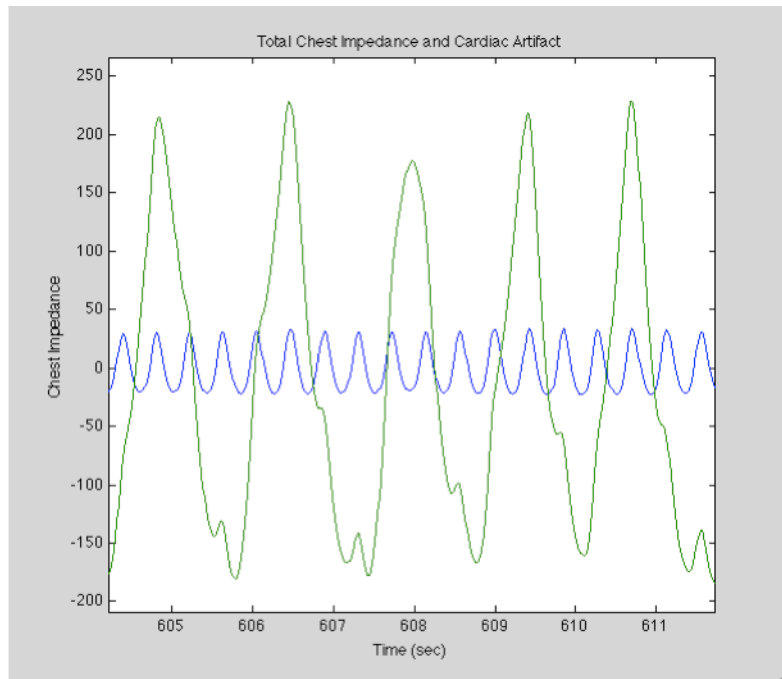
Figure 1: The larger amplitude signal is the total chest impedance and the smaller amplitude is the filtered cardiac artifact. The timescale is roughly eight seconds.

Specific Goals

The goal of this research is to examine whether cardiac output can be reliably measured using the cardiac artifact found in chest impedance signals. A reliable

measure of cardiac artifact from chest impedance may be a useful diagnostic tool for doctors in NICUs. Providing a noninvasive method of measuring cardiac output would reduce the frequency of dangerous, invasive procedures being performed for premature infants. Additionally, since chest impedance is often already being monitored for every infant in the NICU, it would be helpful to show that cardiac output can be made available without any additional means of measurement.

A second goal is to examine whether the amplitude of the cardiac artifact is a reliable predictor of stroke volume. This would be useful for many of the same reasons given above. If the cardiac artifact can give an accurate prediction of cardiac output, then the correlation of the amplitude of the cardiac signal with stroke volume would be helpful in explaining this result and giving a theoretical understanding of this phenomena.

Methods

In order to test whether the cardiac artifact can give a reliable measure of the cardiac output, it will be compared to an accepted method of measuring cardiac output. Studies[iv] have shown that, in direct measurements of arterial blood pressure, stroke volume has been shown to behave according to the following relation:

$$SV = k*(SBP – DBP)/(SBP + DBP) \hspace{3cm} (1)$$

where SBP is the systolic blood pressure, DBP is the diastolic blood pressure, and k is a constant of proportionality. As stated earlier, stroke volume is related to cardiac output by

CO = SV*HR   (2)

where HR is the heart rate.

The cardiac output will be calculated for a database of twenty premature infants. The vital signs of these infants were monitored throughout their stays in the NICU. The vital signs include heart rate, respirations, and arterial blood pressure. Both the instantaneous and the two-second-averaged arterial blood pressure were measured.

Both the averaged arterial blood pressure and the instantaneous arterial blood pressure will be used to calculate two different measures of the cardiac output using the formulae above. These measures of cardiac output will be used as the accepted values against which the cardiac artifact method will be compared.

The method for obtaining the cardiac artifact involves filtering it from the chest impedance signal. Using an established algorithm, the cardiac artifact can be extracted from the overall chest impedance. Figure 1 shows the total chest impedance waveform plotted with the filtered cardiac artifact waveform. A spectrogram function will be used to measure the spectral density of the cardiac artifact signal, particularly at the frequency of the heart rate. A spectrogram uses a sliding window function to sample the cardiac artifact for a localized time and take the Fourier transform of the sampled signal. Using a spectrogram function, the cardiac output will be estimated as proportional to the amplitude of the transform at the frequency corresponding to the heart rate.

Another possible means of estimating the cardiac output from the cardiac artifact is by measuring the standard deviation of the signal. This method will also be tested for agreement with the values obtained from the arterial blood pressure calculation.
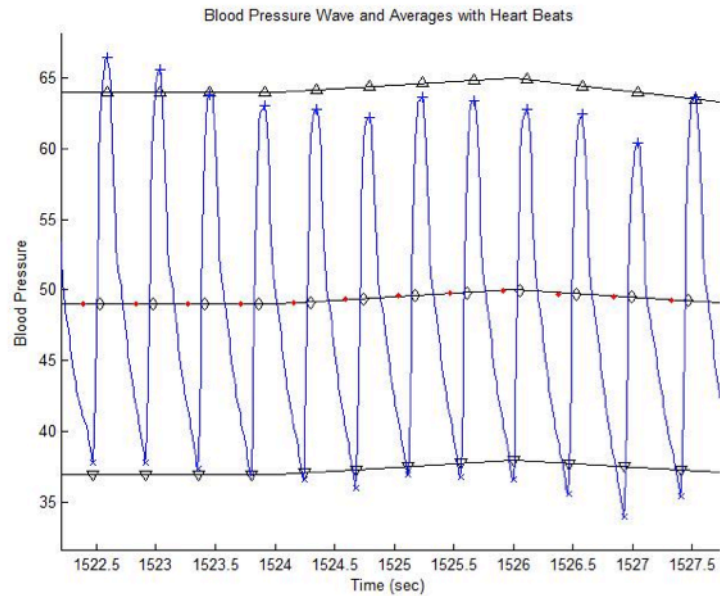
Figure 2: This graph shows the arterial blood pressure waveform plotted with the two-second-averaged systolic, diastolic, and mean blood pressure.

Current Status

Data for twenty four neonatal infants has been obtained from a database. An algorithm has been written to calculate both the stroke volume and the cardiac output from the blood pressure data. Both the blood pressure waveform data and the two-second-averaged data can be analyzed by these algorithms. The program is not yet complete, as there are problems with noisy and incomplete data that need to be addressed.

The heart rate plays an important role in the algorithm that calculates cardiac output from stroke volume, but there are cases where the heart rate detector that was used to collect the data failed to record heartbeats at certain

times. This problem can be addressed by defining an acceptable range in which interpolation of the missing heartbeat is appropriate, and omitting data for cases that do not fall within the safe range of interpolation. The algorithms necessary to accomplish the task of interpolating heartbeats have been written but need formal testing to determine the acceptable range of interpolation.

A spectrogram algorithm has been written that can be tested on the cardiac artifact data. The algorithm for extracting the cardiac artifact from the chest impedance can be applied to the twenty four infants from the database. The spectrogram algorithm along with the standard deviation function will each be used to produce signals approximating the cardiac output from the cardiac artifact.

Future Work

If the cardiac artifact signal is found to be useful in calculating the cardiac output, it may be used to study the relationship between cardiac output and sepsis in neonatal infants. Chest impedance is recorded for all infants at UVa Medical School's NICU and stored in a database. By looking back at the chest impedance signals from infants who have been clinically diagnosed with sepsis, the behavior of the cardiac output could be analyzed to see if any predictable characteristics appear in the cardiac output prior to, or during, the infection.

[i] A. C. Guyton & J. E. Hall, *Medical Physiology*
[ii] "Understanding cardiac output," J. Vincent, *Critical Care*
[iii] "Periodic heart rate decelerations in infants," A. A. Flower et al., *Experimental Biology and Medicine*
[iv] "The cardiac output from blood pressure algorithms trial," J. X. Sun et al., *Critical Care Medicine*