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Computational Model of a Left Ventricle: Showing the Effects of Inertia on Cardiac Dyssynchrony

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Ronald Ulseth, P.E., Faculty Mentor (Co-Director, Iron Range Engineering)

In an effort to research heart failure, a leading cause of death in the industrialized world, this research team has developed a segmented lumped parameter model of the left ventricle. The computations model developed focuses on dyssynchrony, a heart condition where some regions of the heart vary significantly in properties like internal muscle resistance, mass, or elastance. Inertial effects are often assumed as negligible by cardiovascular models. One primary function of this model is to investigate inertial effects as they relate to mechanical cardiac dyssynchrony. An added dimension of this analysis is to observe the thermodynamics of the cardiac cycle as one long term indicator of heart failure. This model was developed using an electrical analog to the hemodynamic system. The parameters of a heart wall segment were represented by resistance, inductance, and capacitance. The calculations were done using state space and programmed into Matlab for simulation. This research shows waveforms of volume outputs as well as pressure volume loops for synchronous waveforms as well as dyssychronous waveforms caused by a time delay, varied resistance, varied elastance, and varied mass. The variation seen in the mass dyssynchrony waveforms suggest that inertial effect may be a significant factor in modeled cardiovascular systems.

Background

Heart disease is a leading cause of death in the industrialized world. Finding effective ways to investigate, diagnose, and treat heart disease and its causes has long been a difficulty in the area of biomedical engineering. There are several methods to investigate heart conditions including human testing, animal testing and computational modeling. Because live testing is dangerous, difficult, and often inconsistent, greater emphasis has been placed on the importance of computational modeling. There are a multitude of benefits to modeling, but by far the most significant is the ability to maintain consistent testing parameters: This allows investigators to develop models that can be easily modified, improved, and expanded upon in order to perform different and valuable investigations. The research team has focused on the development of a segmented lumped parameter model of the cardiac system. Lumped parameter modeling is a method of taking the cardiac system, dividing it into regions and representing each region with a set of parameters (i.e. pressure or resistance).

One common cardiac condition is dyssynchrony where some regions of the heart vary significantly in property from the rest of the heart wall. There are two archetypes of dyssynchrony: electrical dyssynchrony, caused by a localized delay in the electrical signal telling the heart to beat, and mechanical dyssynchrony, caused by a small area of the muscle having unique properties such as increased mass. The scope of this project will only discuss mechanical dyssynchrony; dyssynchrony caused by a delay of certain regions of the muscle will be viewed as a mechanical property alteration, with no investigation into any electrical cause of the time delay. Several models created to investigate mechanical cardiac dyssynchrony (MCD), were made under the assumption that the viscoelastic properties of the muscle may be ignored. Viscoelastic properties of the muscle include the elastance as well as the internal muscle resistance and how that can change with time depending on pressure. More recent research, most notably by Saterlee, contends that “viscoelastic properties should be taken into account.” Several studies have been done in the area of MCD under the claim “the use of viscoelastic and elastic parameters ensure accuracy.”

Another arguably significant property of heart tissue has long been written off as having negligible effects. The inertia of the heart wall and blood moving through arteries and veins has been considered negligible by every model reviewed. It is the assumption of this project that mass of the blood and heart wall segments could play a significant role in MCD. Although no available research is in agreement with this contention, this study will examine the effects of inertia in the cardiovascular system.

Background research into the measurement of MCD has also exposed some deficiencies in the area of cardiovascular engineering. The current methods for measuring MCD include tissue Doppler imaging (TDI), magnetic resonance imaging (MRI), and the use of a conductance catheter to measure the internal flow fraction (IFF). IFF is defined as the total internal flow as a percentage of volume ejected during a beat of the heart. Due to the cost of the first two procedures, the conductance catheter is most often used. The deficiency in measuring dyssynchrony from IFF is that it depends upon the volume ejected from the heart, when in reality dyssynchrony is not dependant on ejection. A purely isovolumic beat as shown by a conductance catheter still has the potential to be in dyssynchrony. Research suggests that this is one of the areas where inertial effects are suspected to play a significant role. In a system with MCD, mass is suspected to attribute significantly to the flow of blood back and forth within the ventricle. For this reason a computation model was chosen.

Computational models of cardiac systems are facilitated by the use of analogs to familiar components. The two most commonly used analogs for the hemodynamic system use electrical and mechanical components. The team's research utilized an electrical analog, where blood pressure is equivalent to voltage, blood flow is current, and volume equates to charge. Resistors are used to represent hemodynamic resistance and inductors represent the masses of muscle tissues and the blood moving through the system. As muscles contract, pressure is induced on the surrounding fluid; this can be modeled by a capacitor with a steady-state time varying capacitance. Capacitors also represent the blood vessels ability to stretch in response to changing pressures within the cardiac system. By altering the properties of and electrical analog an accurate computational model can be developed.

Another area of research in cardiovascular systems has been in the area of the thermodynamics of the cardiac cycle. Shiable's work investigates the work, power, and efficiencies of the cardiovascular system. Efficiency changes due to dyssynchrony are a good, long-term predictor of heart failure due to the effects of cardiovascular remodeling (CR). No background research was forthcoming in the areas of MCD on efficiencies of the heart. The research team believes the effects of MCD on efficiencies in the heart is a property that should be investigated as it is likely an early sign of long term heart failure due to MCD. Since efficiency is work input over cardiac output, and cardiac output must remain constant, when the efficiency of the heart goes down, work must increase. This will cause a long term thickening of the heart tissue, either it is localized, causing further dyssynchrony, or globalized, causing further work losses. Either of these results will continue this downward cycle, building upon each other until heart failure occurs. When the heart undergoes remodeling, which is a change in properties in response to conditions; it is increasing in size and viscoelastic resistance. It has been observed that the increased resistance decreases cardiovascular performance. Based on the research of cardiac mechanics, an increase in mass, especially localized increases, could cause a significant addition to energy losses.

Methods

The team's research was done through the creation of a computational model of the cardiac system. This was done through the creation of an electrical analog, shown in Figure 1, facilitating the creation of our equations. The components in this analog were designed to represent certain parts of the cardiovascular system and certain part of its behavior. The behaviors that the research team modeled were the viscoelastic and inertial properties of the muscle, reactive pre-load and after-load, inertial effects of the fluid, as well as the resistance and elastic properties of the veins and arteries. The model developed allowed for ability to analyze for the thermodynamics of the system by calculating work, power, and efficiency. Key elements of the electrical circuit were chosen to mimic the behavior of several parts of the cardiovascular system, namely the muscle elements, the components representing inflow and outflow, and those representing the circulatory system. These elements were designed to as accurately as possible to mimic the physiological responses of a human cardiovascular system.

The muscle tissue was designed based on a three-element windkessel model. A windkessel can be modeled as an electrical analog for the muscle tissue properties using a resister, inductor, and variable capacitor placed in series. The resistor shows the internal muscle resistance, the inductor represents the mass of the muscle tissue, and the variable capacitor models the muscles ability to contract. The variable capacitance function is time varying function, and repeats in a steady state cycle. The input function is a sine wave, which has been half wave rectified, smoothed and biased a small amount to accurately represent the contraction of a heart. The flat parts of the wave model the relaxation period of the heart, and the pulses represent the heartbeat. Any number of these can be connected into a common node, and in this model there are four heart wall sections.

The inflow and outflow elements are very similar. Flow through a heart valve can be modeled by a resistor, diode, and inductor in series. The resistor is seen as the hemodynamic resistance to flow through the valve. The diode only lets flow through on direction, as a valve would in a real system. The inductor represents the inertia of the fluid moving through the valve. The rest of the circuit represents the veins and arteries. The system resistance (resistance in veins and arteries) is modeled by a resistor. The veins and arteries modeled with compliance, or, the ability to stretch in response to changes in pressure, allowing for slight changes in diameter and volume. A capacitor allows for the storage of charge as the veins or arteries would store blood as the pressure is altered. Another component is a small voltage reader in the form of a capacitor with a very small capacity, which will affect the volume negligibly, yet give an accurate reading for the voltage developed in the ventricle.

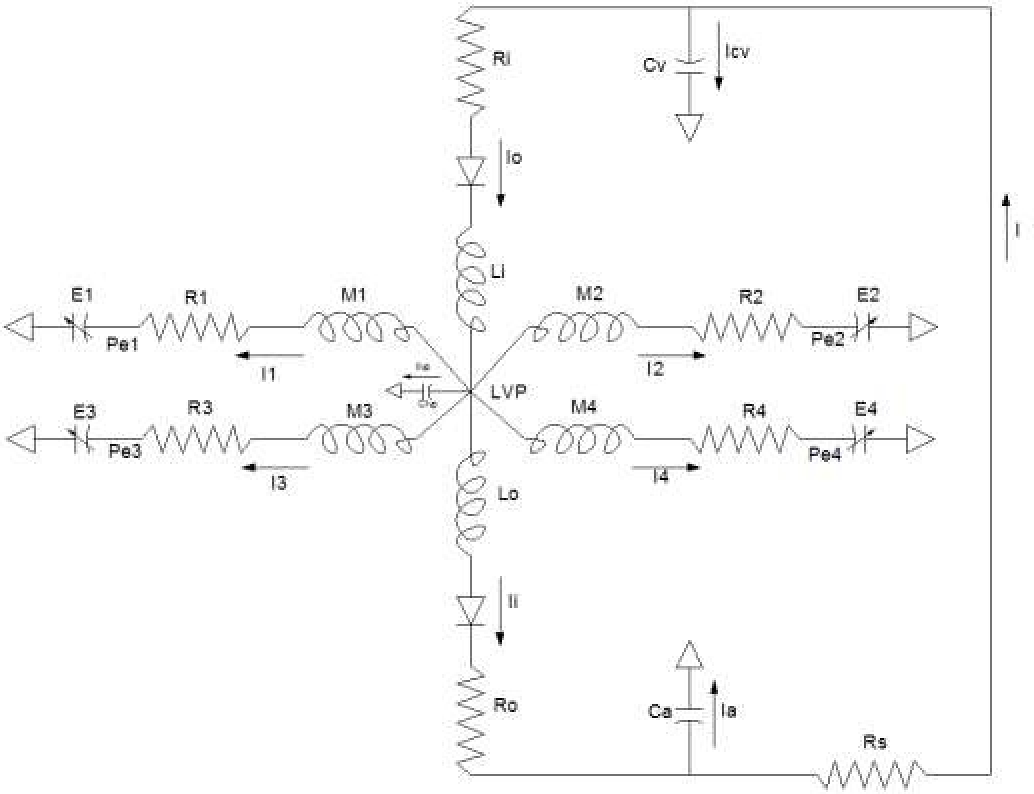

Figure 1 : Electrical Model of the Heart

The computational model was created from a series of equations generated from the analysis of the electrical circuit. These equations were generated using the state-space technique is based on creating one equation for each energy storage device. The result was a series of second order differential equations. To solve these equations, a program had to allow for quick and repeated calculations, but can also be modified easily for different effects on the heart.

Matlab was chosen because it allowed for robust computational analysis of the research team's cardiac model.

Results and Discussion

The results from the research are waveforms of a cardiac system in synchronous and dyssynchronous modes. Two types of waveforms are shown, volume waveforms, showing the amount of volume in each segment of the heart, and pressure-volume loops. An easy way to identify dyssynchrony is to use these waveforms because each segment is not identical. By analyzing the segments of the heart wall, different properties are seen resulting in internal flow. Pressure volume loops can be used in the same way, but also show the work being done by the entire heart as well as each segment. This can help identify a segment which will be under a higher load which could eventually cause heart failure. The waveforms make it possible to view each segment of the heart versus the total output. This is important because today's technology does not measure small increments of the heart but only measures the total output.

During the course of this research many different kinds of MCD were modeled. One major cause of dyssynchrony is due to a time delay of one section of the heart wall. The other major kind of dyssynchrony occurs when one of the heart wall segments becomes stronger or weaker than the others, called elastance dyssynchrony. Another type of dyssynchrony happens in a heart where some of the muscle has been thickened and it has a highly increased internal muscle resistance. The last type of dyssynchrony can occur when a section of the heart wall has a higher mass than the other sections, even if altered resistance, muscle strength, or timing is not experienced.

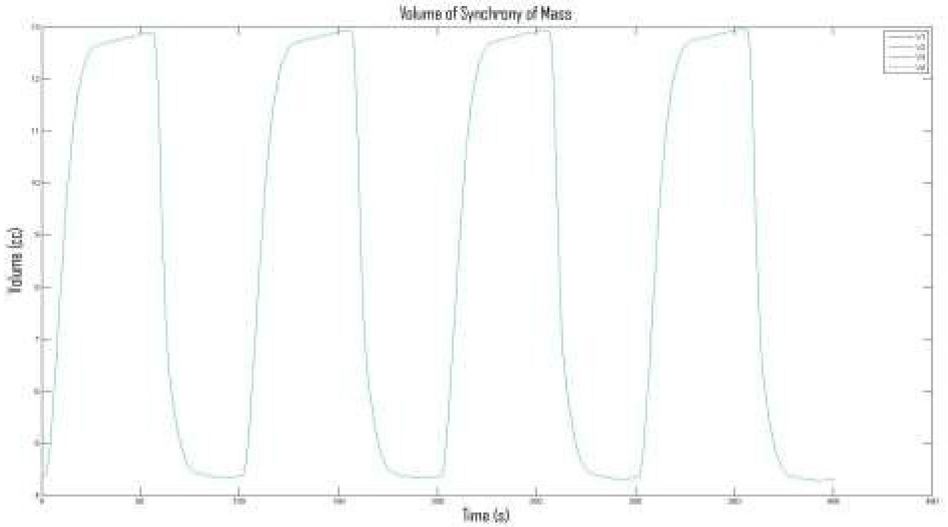

Figure 2 : Synchronous volume waveforms

Shown in Figure 2 is a synchronous (healthy) waveform comparing volume versus time. This waveform shows four heart beats, and, for each, it can be seen that there is a significant increase in volume when filling occurs, and then a short period with relatively small changes in volume, where the filling slows and halts. At the end of this period there is a very small section with no volume change, where the ventricle is undergoing contraction before ejecting rapidly. This ejection then slows and stops until the cycle repeats itself. In this graph there is one waveform representing each of the ventricle wall section, and they are identical. Because of this they lay on top of one another and only one is seen.

Figure 3 shows the same configuration of parameters, but this graph displays pressure versus volume. By comparing pressure and volume, the work done is determined by the size of the area shown inside the loop. The graph shows all four heart wall segments, once again identical, as well as the pressure-volume (PV) loop for the entire left ventricle. The bottom section of the P-V loop is where the filling occurs; increasing in volume until isovolumic contractions begins. Isovolumic contraction climbs up the right side of the loop, and transitions to ejection where volume decreases along the top. During isovolumic relaxation the pressure rapidly decreases and at its conclusion the cycle repeats itself. The large loop represents the combined work of each heart section in the left ventricle. The smaller loop indicates the work done by each individual segment.

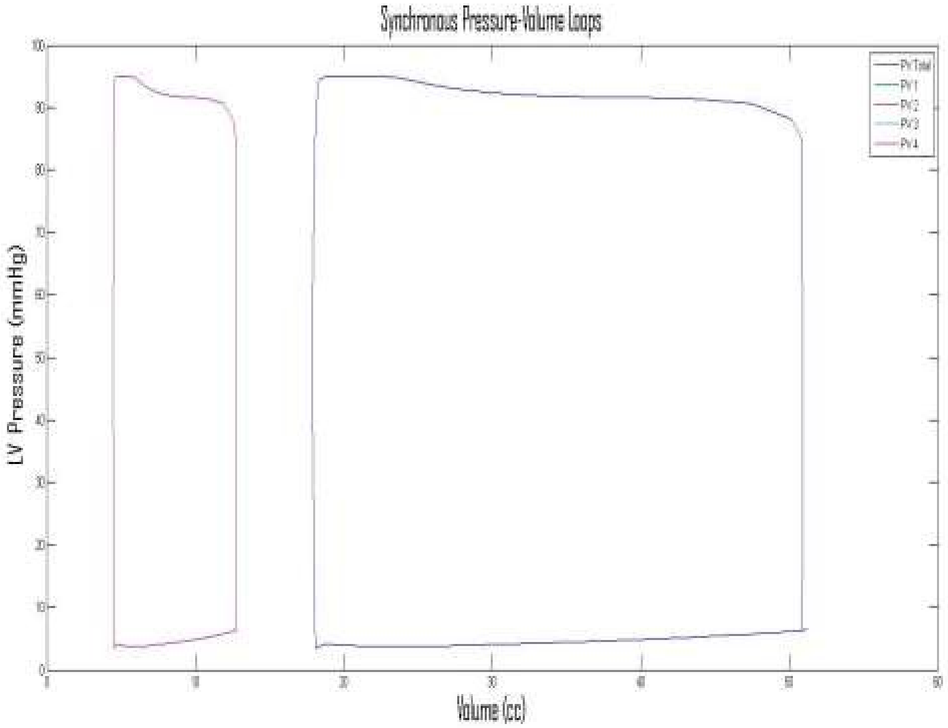

Figure 3 : Pressure - volume loops in synchrony

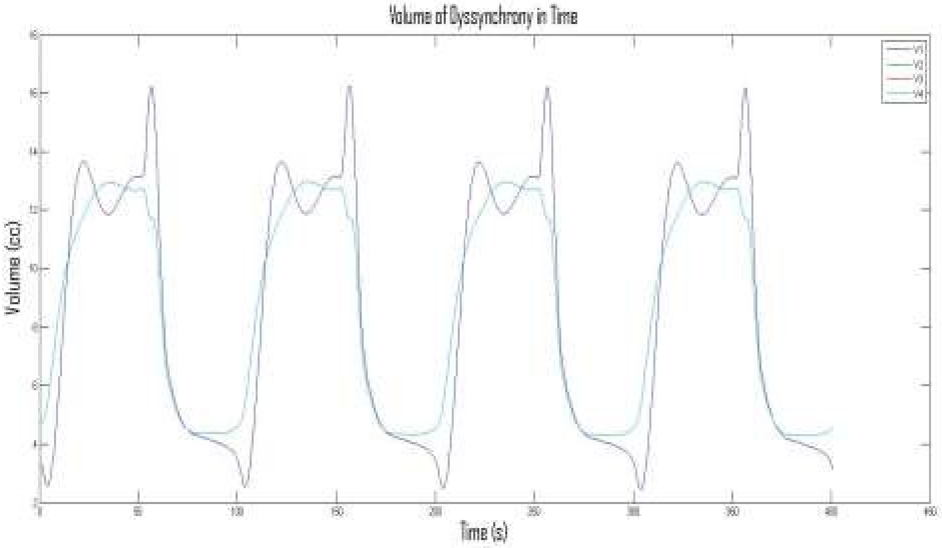

Figure 4 : Time dyssychronous volume waveform.

Figures 4 and 5 show a left ventricle beating in time dyssynchrony. On the volume waveform it can be seen that one of the waveforms moves much more than all the others. This segment of the heart wall, due to a .01 second delay is pushed in and overcompensates, moving mush more than the others in order to balance pressures with the other heart wall sections. By observing the work diagram it is also shown that one section of the ventricle is doing much more work than the other sections. This is going to cause unhealthy development in this heart.

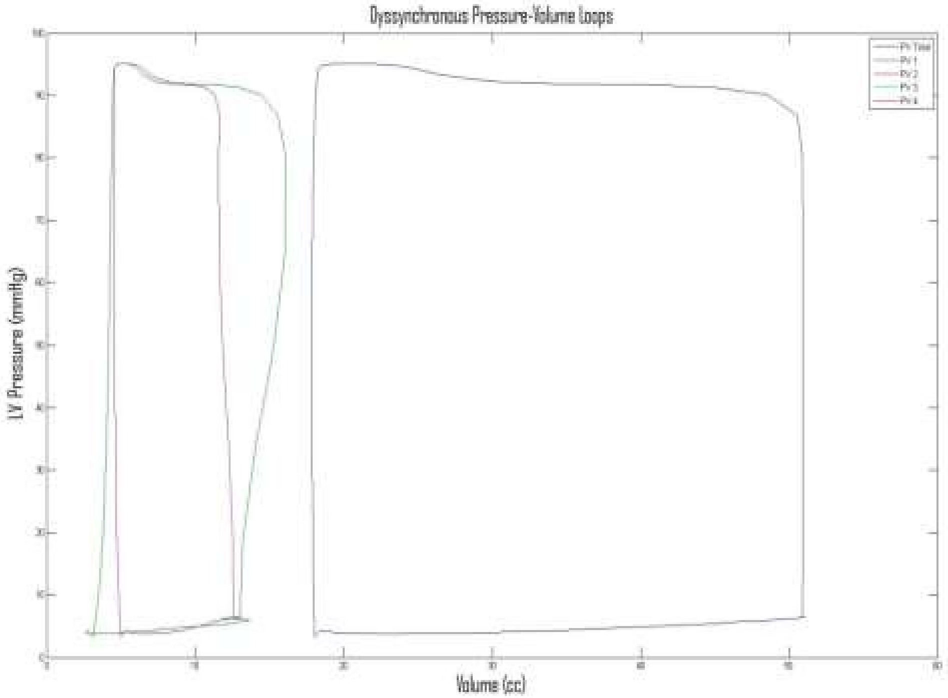

Figure 5 : pressure volume loops for time dyssynchrony

Another common form of dyssynchrony can be caused by an increase in elastance. In Figure 6 we can see the effects on volume of due to and increased elastance in one section of the heard wall. Most of the differences are seen on this graph during the times of minimal volume change. Figure 7 shows the effect of elastance dyssynchrony on the pressure volume loop. Once again there is a difference in work done by this ventricle but surprisingly, even though the elastance on this section is higher, the work decreases. This is because the section cannot relax as much and therefore has less volume to move.

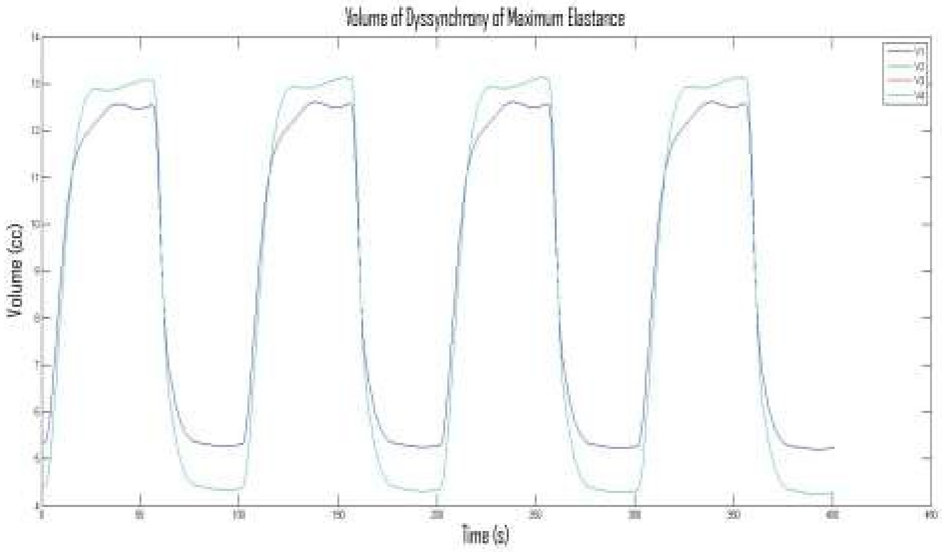

Figure 6 : volume waveforms for elastance dyssynchrony

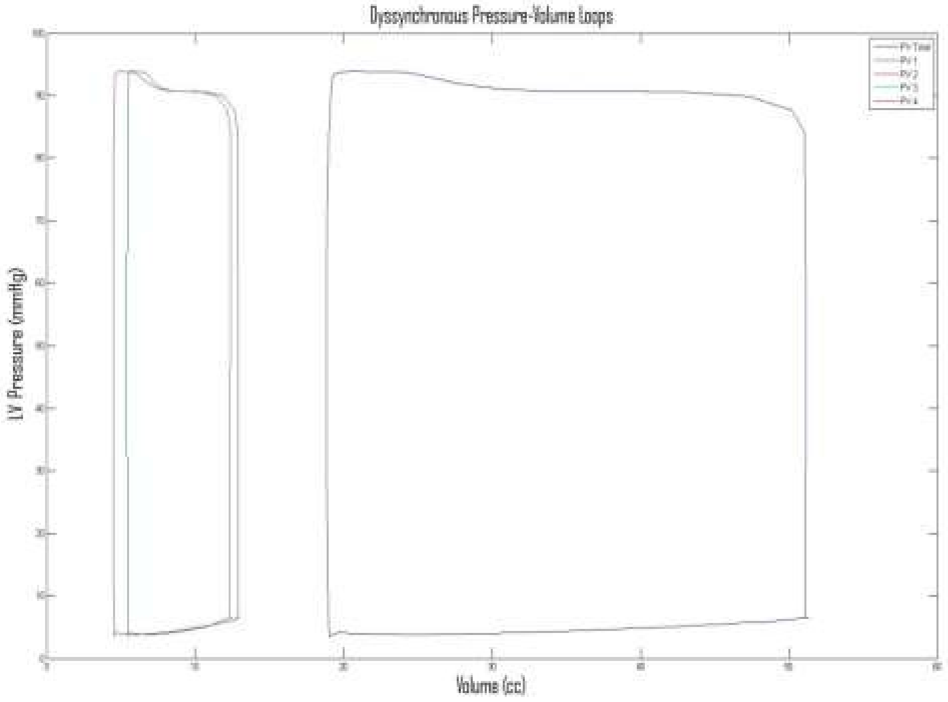

Figure 7 : pressure volume loops for elastance dyssynchrony

Figure 8 displays the effects of resistance dyssynchrony upon the volume changes in the heart. The curves are due to the increase in the muscles internal resistance, it takes longer for the muscle to move due to the same pressure. Even with this huge difference, there is very little effect on the pressure volume waveforms for resistance dyssynchrony as shown in Figure 9.

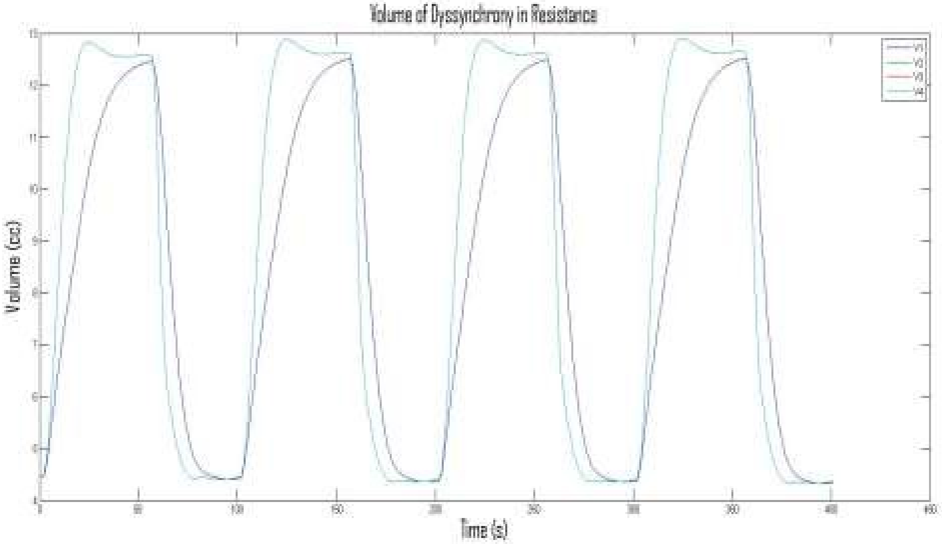

Figure 8 : volume waveforms for resistance dyssynchrony

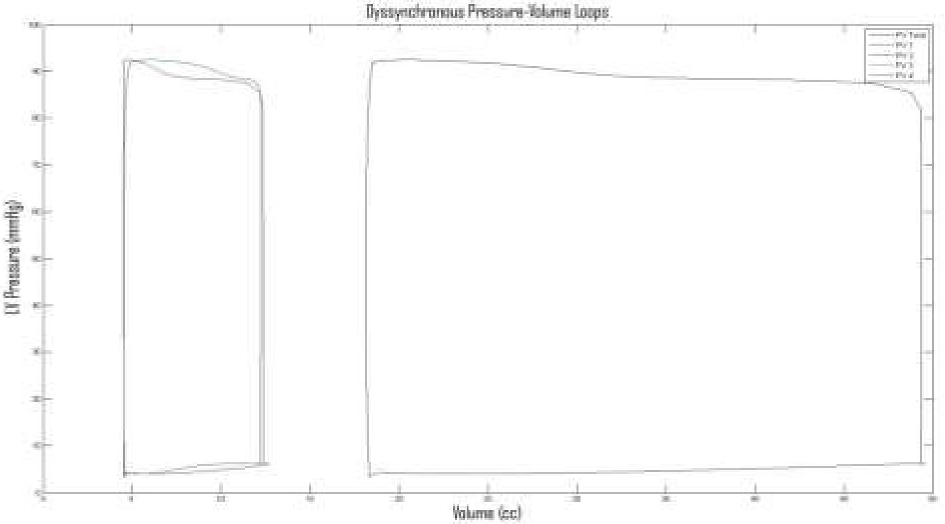

Figure 9 : pressure volume loop for resistance dyssynchrony

No work had been forthcoming identifying the existence of a dyssynchrony in the heart due to an increased mass in a section of the heart wall. The model developed by this research team incorporated dyssynchrony and allowed for the display of the effects of differences in mass on the left ventricle. Not only can dyssynchrony exist due only to mass discrepancies in the terms of volume changes on the heart this dyssynchrony appears significant (Figure 10). When looking at the pressure volume waveforms, almost no difference is seen between the section with differing characteristics and the others (Figure 11). Whether or not the effect of this form of dyssynchrony occur on the pressure volume waveforms, the difference can be seen on the volume graphs, and this internal flow may cause significant health issues.

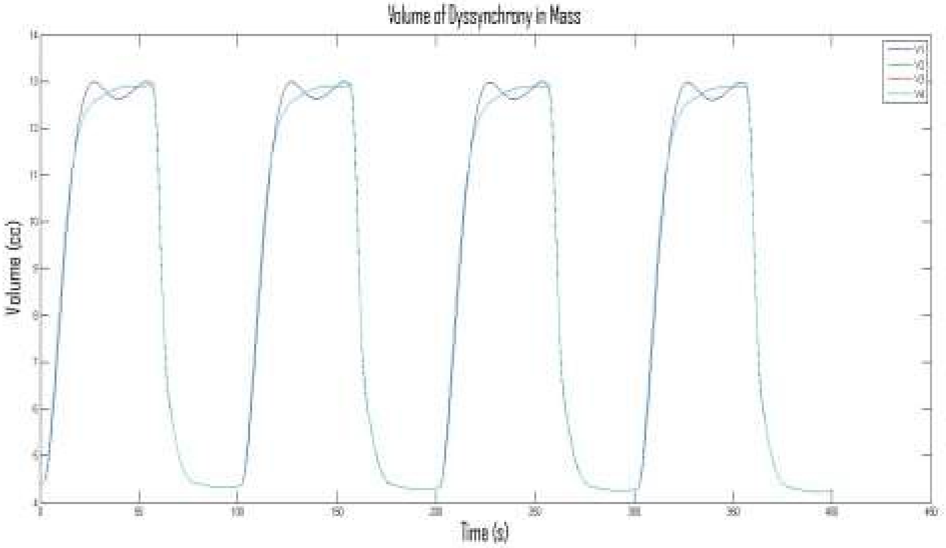

Figure 10 : volume waveforms of mass dyssynchrony

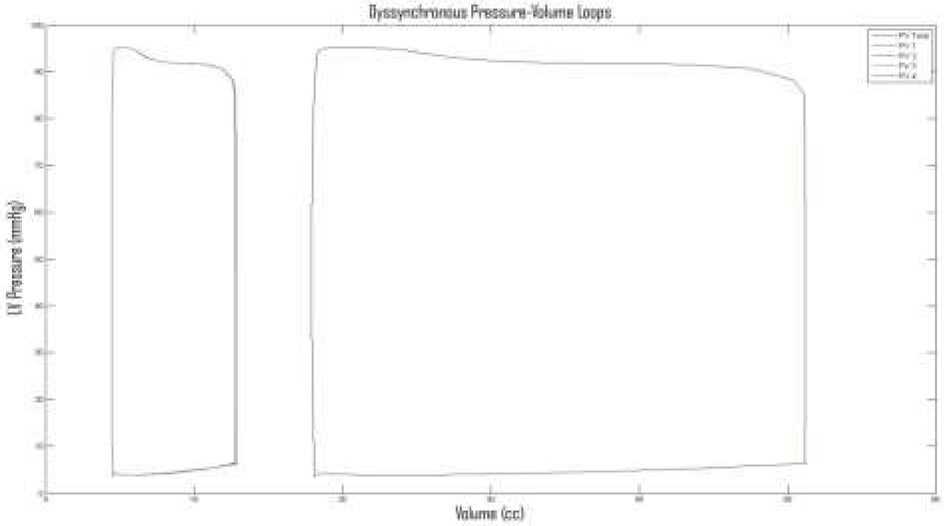

Figure 11 : pressure volume loops for mass dyssynchrony

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MATTHEW KORPELA, from Squaw Lake, MN, is currently attending Iron Range Engineering, a new upper division program from the University of Minnesota – Mankato. He interned for the Minnesota DNR where he used ArcGIS software for interpolating photographs across Minnesota. He also took part in undergraduate research in astrophysics from the University of Toledo. There he studied the newly defined Be star “Delta Scorpii” and the H-alpha lines that were being emitted, under the supervision of Dr. Karen Bjorkman, Department Chair and Ph.D. The days after graduation may lead him in many directions, but he is currently perusing a career in Biomedical Engineering.

ERIN LAMKE, from the small northern Minnesota town, Hill City, is attending Iron Range Engineering (IRE), a program through Minnesota State University – Mankato. Erin is studying Engineering (mechanical) and will graduate with her B.S.E degree in December 2011. Erin spent the summer interning at Medtronic for the Perfusions Systems Supplier Quality Engineering group where she helped to drive quality and continuous improvement to deliver excellence in products, processes, services and relationships. Erin was asked to stay on and will be co-oping part time for her final semester at IRE. Upon graduation Erin hopes to continue her career at Medtronic and attend grad school to get her MBA.

ANDREW MCNALLY, from Chisago City, MN, is attending the Iron Range Engineering program at Minnesota State University – Mankato. Andrew is studying to complete a B.S. in Engineering with emphases in mechanical engineering an biomedical engineering, in December 2011. Andrew Spent the summer interning at Medtronic for the Perfusion Systems Manufacturing Engineering group where he helped to support several product lines, worked to implement various process improvements, and lead a project to replace a piece of capital equipment. Upon graduation Andrew plans to work for several years in order to build some experience, then to seek master’s degrees in the areas of mathematic and biomedical engineering. His ultimate career goal is to become an engineering educator.

MATT HUDSON, from Shoreview, MN, is currently a senior studying engineering (mechanical) at Iron Range Engineering, a Minnesota State University, Mankato program. Matt, along with his business partner Eric Schaupp, recently won the 2011 Student Division of the Minnesota Cup entrepreneurial competition. With the guidance of Dr. Dan Ewert and Dr. Queen Booker, Matt researched a new, innovative approach to portable power generation. Upon graduation in May 2012, Matt will begin working as an engineer at Procter & Gamble in Cincinnati, Ohio.

RON ULSETH, P.E. is a faculty member in the Itasca Community College Engineering and the Iron Range Engineering programs. He has been in the classroom, teaching for more than 20 years and has been a contributor to the development of both programs. Additionally, Ulseth recently retired after 24 years in the US Navy Reserve as an Engineering Officer.