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Pneumatic artificial heart driver parameter effects on the rate of pressure change ((+) dP/dt max)

Henker, Richard Alynn, M.S.

The University of Arizona, 1987

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PNEUMATIC ARTIFICIAL HEART DRIVER PARAMETER EFFECTS ON THE RATE OF PRESSURE CHANGE ((+) dP/dt max)

by

Richard Henker

A Thesis Submitted to the Faculty of the

COLLEGE OF NURSING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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Carolyn Murdaugh — 6/30/87

CAROLYN MURDAUGH
Associate Professor of Nursing

Date

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ABSTRACT

The aim of the research was to investigate the effects of three parameters of the artificial heart on the (+) dP/dt max. The study was conducted using a mock circulation which was connected to an artificial heart. The data were collected using the COMDU software developed for the computer which monitors the artificial heart.

Stepwise regression analysis was utilized to test the three hypotheses. Two of the null hypotheses for the study could not be rejected, as the independent variable did not significantly affect (+) dP/dt max. Although the third hypothesis was accepted, the results were not clinically significant. Limitations in the study were multicollinearity among the independent variables, small sample size, and the inability of the mock circulation to represent human responses.

CHAPTER I

INTRODUCTION

The artificial heart is being used more frequently in clinical practice as a bridge to transplant. The option of the artificial heart is reasonable because of the lack of readily available donor hearts (Henker, Shaffer & Whittaker, 1985). Patients who qualify for use of the artificial heart as a bridge to transplant include patients who experience acute rejection after receiving a heart transplant, and transplant candidates whose condition deteriorates rapidly when a human heart is not readily available. In both of the above situations the artificial heart can sustain life until a human donor heart is obtained for transplant.

The artificial heart, a pneumatically driven mechanical device, consists of two hemispheric ventricles that are made of polyurethane with a flexible pumping diaphragm and four tilting disc valves. The inner lining is manufactured without seams. Dacron grafts are used to connect the patient's pulmonary artery and aorta to the artificial heart. Atrial cuffs connect the remnant atria to the polyurethane ventricles. During surgery the dacron grafts and atrial cuffs are sutured into place. The ventricles are then snapped into place with quick connects (Quaal, 1985). With every contraction air inflates the diaphragm in each ventricle. The diaphragm pushes the blood out of the ventricles (Quaal, 1985). The diaphragm moving the blood out

of the ventricles causes an increase in intraventricular pressures. The design of the valves and the quick connects promotes turbulent flow in the inflow and outflow tracts. The increase in intraventricular pressure with resultant turbulent flow can lead to complications resulting in serious bodily impairment or death.

Effects of the Artificial Heart on Thrombus Formation

Thrombus formation is the most frequent complication in the artificial heart. In 57% of the patients who have received an artificial heart implant stroke has occurred (Levinson, et al., 1986a). Thrombus formation in the artificial heart occurs around the artificial valves or in the area of the quick connects (Quaal, 1985). Thrombus formation in the artificial heart patient can be caused by a variety of factors: increased platelet aggregation, crevices in the valve flow rings, crevices in the quick connects, thrombogenicity of the device, resistance to heparin, and decreased cardiac output (Levinson, Smith, Gallo, Cork, Emergy, Icenogle, Ott & Copeland, 1986b). The damage to red cells and platelets from the increased intraventricular pressure also leads to increased potential for thrombus formation (Oiknine, 1983). Hardwick, Gritsman, Stromberg & Friedman (1983) measured platelet response after shear stress was applied with a viscometer. The result was an increase in platelet aggregation (Hardwick, Gritsman, Stromberg & Freidman, 1983).

Measurement of Artificial Heart Parameters

Cardiac output produced by the artificial heart can be continually assessed by a computer that measures airflow and pressures in the drive lines from the drive system (Willshaw, Nielsen, Nanas, Piches & Olsen, 1984). The computer uses software designed exclusively for the artificial heart. The software is labeled Cardiac Output Monitor and Diagnostic Unit (COMDU) (Symbion, Inc., Salt Lake City, Utah) (Willshaw, Nielsen, Nanas, Piches & Olsen, 1984). The COMDU program within the COMDU software allows the visualization of the filling wave form as blood enters the ventricle. The program also displays the pressure wave form that is needed to completely eject the blood from the ventricles (Quaal, 1984).

The COMDU software has numerous programs which enable other variables to be monitored. One program monitors the rate of increase of the intraventricular pressures, termed (+) dP/dt max. Other variables, i.e. cardiac output, filling volume, drive pressure waveforms, filling waveforms, cannot be measured when the program is in use. The only value obtained while in this program is (+) dP/dt max measured in millimeters of mercury per second (mmHg/sec). The positive derivative of pressure/derivative of time maximum (+) dP/dt max is the maximal rate of left ventricular pressure development (Wallace, Skinner & Mitchell, 1963). The (+) dP/dt max is obtained by measuring the rate of pressure change of the air entering the ventricles of the artificial heart. The (+) dP/dt max is only measured on the left side of the heart because of the higher pressures needed to eject blood

against the systemic circulation. The rate and pressure with which the air enters the ventricles of the artificial heart are controlled by three mechanisms: heart rate, percent systole, and right and left sided drive pressures. These parameters control the filling of the ventricles and the ejection of the blood from the ventricles.

Levinson et al. (1986c) conducted a retrospective study comparing 15 artificial heart patients. Two groups of patients were observed: patients utilizing the Utah Drive System I (Symbion, Inc.) and patients utilizing the Utah Drive System II (Symbion, Inc.). The (+) dP/dt max in the Utah Drive System I was 6000 mmHg/sec to 8000 mmHg/sec, the (+) dP/dt max in the Utah Drive System II was less than 4500 mmHg/sec. Patients with the higher range of (+) dP/dt max have an elevated plasma free hemoglobin, which indicated destruction of the red blood cells. Destruction to platelets would also have occurred at even lower levels since it takes one tenth the pressure to destroy platelets as compared to erythrocytes (Hardwick, Gritsman, Stromberg & Friedman, 1983). The increase in platelet damage would lead to release of serotonin and the potential start of the clotting process (Johnston, Marzec & Bernstein, 1975).

Study Purpose

The aim of the research was to investigate the effects of three parameters of the artificial heart on the (+) dP/dt max. Specifically, the effects of heart rate, left sided drive pressure, and percent systole on the (+) dP/dt max were examined.

Research Questions

The research questions were as follows:

1. What is the effect of a change in heart rate on the (+) dP/dt max?

2. What is the effect of a change in the left sided drive pressures on the (+) dP/dt max?

3. What is the effect of a change in percent systole on the (+) dP/dt max?

Significance

The predominant complication in the patient with an artificial heart is the formation of thrombi that may result in emboli. As previously mentioned, 57% of the patients who receive an artificial heart have experienced a stroke (Levinson et al., 1986a). The damage to platelets and red blood cells predisposes the patient to the formation of the thrombus (Oiknine, 1983). If the pressures in the ventricles can be decreased by varying the artificial heart parameters the predisposition for thrombus formation and stroke may be reduced. Once the problem with thrombus formation is resolved the use of the artificial heart may increase, as the ability to use the device effectively will enable patients to be maintained safely until a human donor heart is found.

Summary

The artificial heart is being used more frequently in clinical practice and is no longer considered only for investigation in the

animal model. The major limiting complication to this point has been the occurence of strokes in patients who have had the artificial heart implanted. Factors that predispose patients to a stroke have been identified. However the interventions needed to decrease the predisposition for stroke need to be researched. This research will investigate the parameters of the artificial heart which may damage the platelets and red cells as damage to these cells leads to thrombus formation.

CHAPTER II

THEORETICAL FRAMEWORK

The theoretical framework describing the effects of the artificial heart on thrombus formation is presented. The relationships between the artificial heart, cardiac performance, and thrombus formation are described. Figure 1 depicts the theorized relationships at the construct, conceptual and operational levels.

Artificial Heart, Cardiac Performance and Thrombus Formation

At the construct level the theoretical framework describes the effects of one mechanical assist device, the artificial heart on cardiac performance which in turn effects thrombus formation. Mechanical assistance in the last 30 years has progressed from the planning stages to clinical use. Mechanical assistance is designed to supplement or replace the heart as a pump (Quaal, 1984). The mechanisms used to accomplish mechanical assistance can be divided into a pulsatile flow mechanism or a nonpulsatile flow mechanism. The devices using pulsatile flow attempt to pump in a manner similar to the contractions of the normal heart. Pulsatile flow provides for adequate kidney perfusion (Bergman, 1979) and adequate peripheral perfusion (Roberts, 1977). However the pulsatile flow devices have limitations. Zumbro & colleagues (1979) found that pulsatile flow increased the amount of damage done to red cells, exemplified by an increase in the plasma hemoglobin.

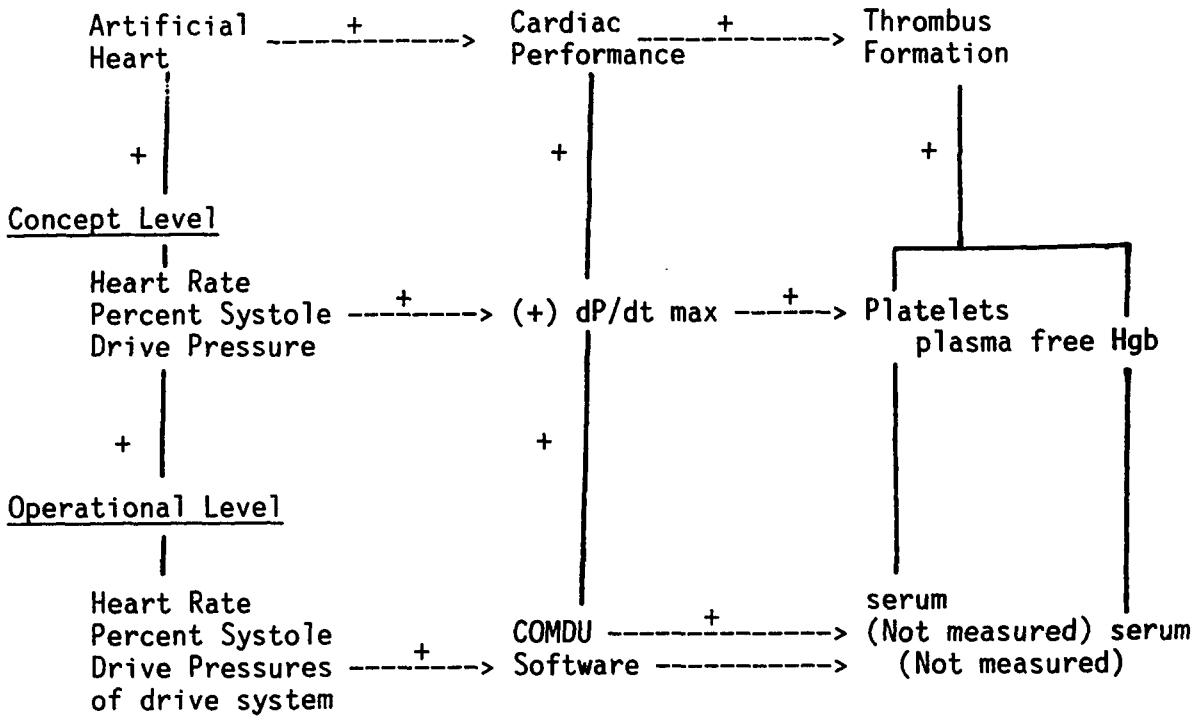

Figure 1. Theoretical Framework

The total artificial heart utilizes pulsatile flow and the Frank-Starling law.

Starling's law is based on the fact that the heart is a muscle that pumps. An increase in the resting fiber length (preload) will augment the force of contraction, increase the extent to which the muscle shortens with the given load, and cause more blood to be ejected. In isovolumetric preparations, increases in preload cause increases in time - to - peak left ventricular pressure or (+) dP/dt max. In the intact heart preload refers to the stresses acting in the myocardial chamber wall at the end of the filling phase (diastole) which determine the length of the myocardial fibers immediately prior to the onset of contraction (systole).

In the isolated heart muscle set at a given length, the velocity of the ensuing contraction is inversely related to the force against which the contraction pulls (afterload). In the intact heart, afterload is the wall stress generated to eject blood from a particular chamber. The greatest afterload occurs when the semilunar valves open, when intraventricular pressures reach the diastolic pressures of the great arteries.

The Frank-Starling law of the heart relates resting fiber length, expressed as end-diastolic volume in the intact heart, to tension generation, expressed as left ventricular pressure development (Guyton, 1986). Clinically, the preload (end-diastolic volume), afterload, the contractile state and heart rate are evaluated to assess cardiac performance.

The artificial heart's ability to increase the cardiac output with an increase in preload can be analyzed from the waveforms obtained from the COMDU. Changes in the drive system which control the artificial heart are made to maintain the Frank-Starling law in the artificial heart. The major principles utilized when analyzing the waveforms and making drive parameter changes are partial fill during diastole and full eject during systole. Please refer to Appendix A for more information on parameter changes. Examples of the waveforms generated from COMDU during diastolic phases and systolic phases are presented in Figures 2 and 3. Once the heart driver is adjusted properly the cardiac output will increase with an increase in preload.

A major consideration when monitoring the artificial heart is the prevention of stasis of blood in the heart. Again the two major principles of the artificial heart apply: (1) the ventricles are not allowed to completely fill and (2) blood must be completely ejected from the ventricle during each contraction. If the heart completely fills, stasis of the blood occurs predisposing the patient to thrombus formation. The same also holds true for ejection. If the blood is not completely ejected there is a predisposition for thrombus formation.

Thrombus formation in patients receiving some form of mechanical assistance is a frequent event. Turbulent flow, statis and injury to blood components affect thrombus formation (Kilgo, Toole & McGhee, 1986). Johnston, Marzec & Bernstein (1975) described the effects of surface injury from shear stress. The damage to the platelets is not significant unless they start to aggregate and release serotonin. These events trigger the formation of a clot.

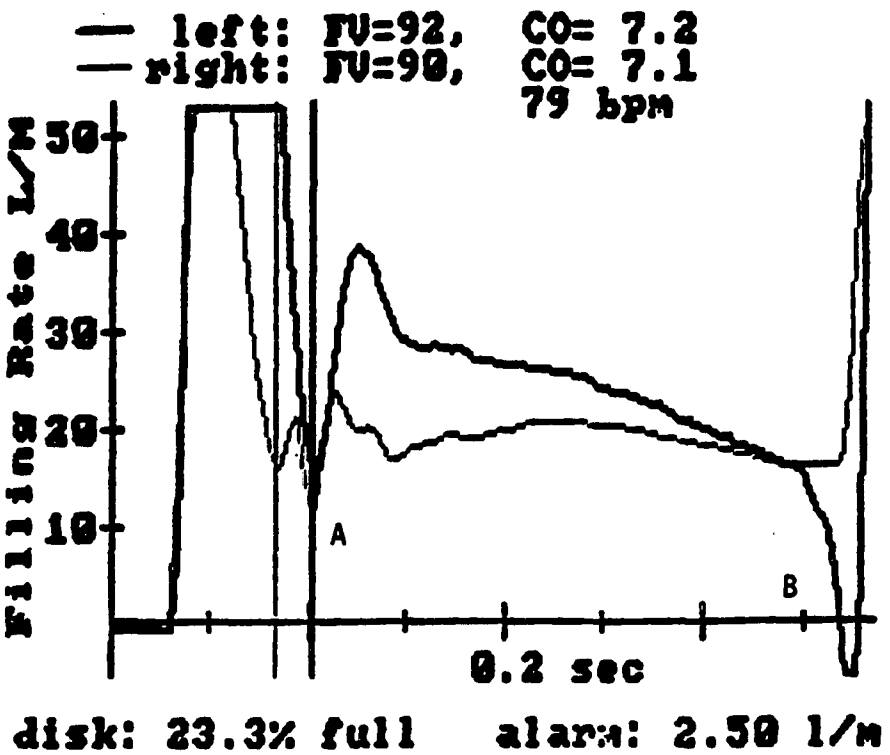

Figure 2. COMDU Waveform. A is the point at which the computer starts measure the filling volume. B is the point which indicates that full fill has occurred.

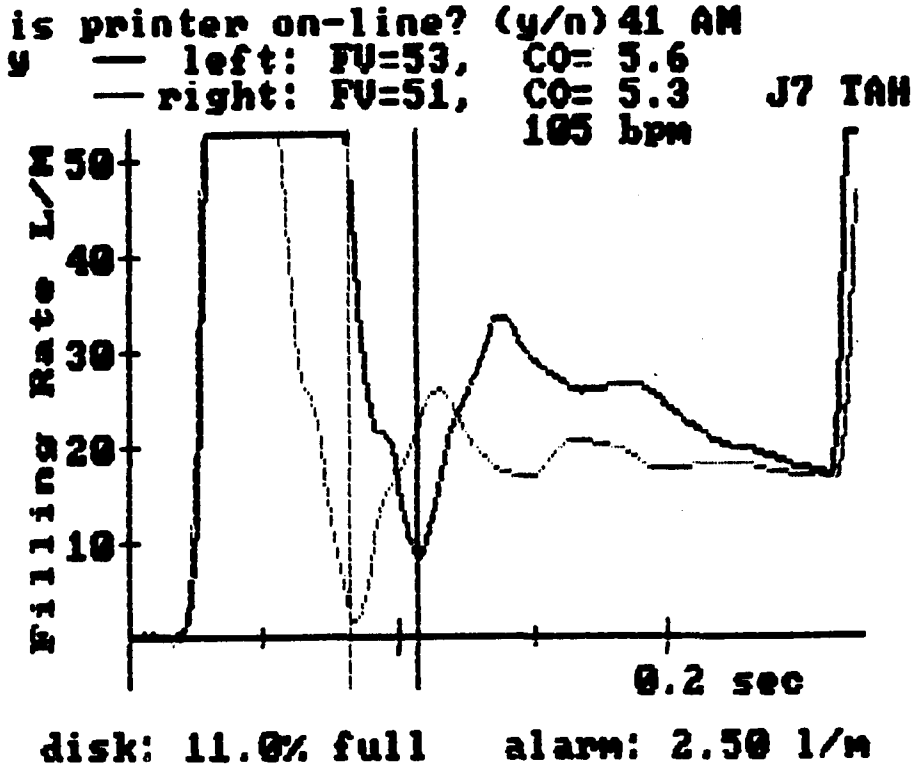

Figure 3. COMDU Waveform. This is an example of partial filling in the artificial heart.

Atsumi (1979) found that only two of 13 goats who had artificial hearts implanted had normal kidneys on post mortem exam. The remaining 11 were found to have thrombus formation in their kidneys. The thrombus formation was associated with the continuous damage to the blood components. The hematocrit in the goats decreased while they had the artificial heart in place.

In animal models that received the artificial heart formation of pannus was a problem. Pannus is a dense fibrous connective tissue found in the calves that received an artificial heart implant (Quaal, 1984). The etiology of pannus formation includes turbulent flow, platelet damage, and use of foreign materials. Modifications in the valves and quick connects were made to decrease the formation of pannus (Jarvik et al., 1981).

In humans pannus formation has not been a problem; the formation of thrombus is the limiting factor when considering use of the artificial heart. The cause of the thromboembolic event in patients can be from a variety of causes. In one patient (Levinson et al., 1986a), thrombus formation was thought to be from a combination of improved liver function, hemoconcentration, decreased flows, inability to maintain adequate heparinization, and thrombogenicity of the device. Olsen (1979) states that mechanical pump advancements have been fraught with activation of the blood-clotting mechanism in patients.

Hardwick et al. (1981) suggest that the exposure of the blood components to artificial valves and to extracorporeal circulatory devices can cause damage to the structure of the platelet and cause thrombus formation. Hung et al. (1976) determined that it takes

one tenth of the pressure to cause red cell damage that it would take to cause platelet damage.

Drive Parameters, dP/dt, Platelet Changes and Plasma Free Hemoglobin

The artificial heart has the capability to control the heart rate, drive pressure and percent systole which are used to circulate blood (Quaal, 1984). Goals in the clinical use of the artificial heart are to prevent the formation of thrombus while maintaining cardiac output. Drive pressures are decreased to prevent red blood cell damage. Heart rate is adjusted to prevent the stasis of blood anywhere in the artificial heart. The most recent studies have shown that heart rate may be the major factor predisposing patients to thrombus formation (Levinson et al., 1986c). Percent systole is set to promote filling and ejection of the blood from the ventricles. Percent systole is used to determine how much time is spent in each phase of the cardiac cycle (Quaal, 1984).

The drive parameters of the artificial heart effect the period of time over which the pressure is increased. The rate of pressure development is referred to on the COMDU program as dP/dt (Willshaw et al., 1984). The (+) dP/dt max as defined by Wallace, Skinner & Mitchell (1963) is the maximal rate of ventricular pressure development. An increase in (+) dP/dt max indicates that the ejection of blood occurs at a faster rate with greater pressure changes causing more damage to blood components.

The mechanisms for RBC destruction in the artificial heart are the mechanical forces of pressure, shear stress, turbulence, and cell wall interactions (Akutsu, 1975). Increasing the shear stress has been shown to increase the amount of platelet aggregation that takes place (Glover et al., 1974). Surface injury that occurs at a perpendicular angle can cause more damage than just shear stress (Johnston, Marzec & Bernstein, 1975). The damage that occurs to the platelets changes their shape. The shape change causes an increase in the platelets ability to aggregate. A change in the shape of the platelets alone does not cause a thrombus to form. Once sufficient stimulation takes place a release reaction occurs and contents of the platelets, ADP, serotonin and calcium are released and the formation of the thrombus is irreversible (Johnston, Marzec & Bernstein, 1975).

The measure often used to measure cell destruction is plasma free hemoglobin (Olsen, 1979). Plasma free hemoglobin measures the amount of hemolysis that occurs because of trauma to the red blood cells. In the past the measure has been used to determine the amount of red blood cell destruction caused by blood pumps. The disadvantage of this measurement is that it does not take into consideration sublethal changes to the cells (Olsen, 1979). In a study done comparing various materials and valves, Olsen (1979) found that smoother materials and fewer artificial valves decreased the amount of plasma free hemoglobin in the serum. Atsumi (1979) found that the hematocrit could be an indicator of the amount of red blood cell destruction taking place. The hematocrit in the 13 goats in his research gradually decreased. The decrease was partially attributed to the four artificial

valves that caused destruction of the red cells. Further development of the artificial heart has decreased the amount of red blood cell destruction that occurs (Jarvik, 1981).

In the patients at University Medical Center in Tucson plasma free hemoglobin has been used to determine red blood cell destruction. In the first patient with a Jarvik-7 artificial heart, the highest plasma free hemoglobin was measured immediately after being on cardiopulmonary bypass. The patient did not have a significant problem with red blood cell destruction but thrombus formation did occur with a resultant stroke.

Hypothesis Tested

A change in heart rate will significantly affect the (+) dP/dt max.

A change in percent systole will significantly affect the (+) dP/dt max.

A change in the drive pressure will significantly affect the (+) dP/dt max.

Operational Definitions

Heart Rate. Number of contractions of artificial heart per minute as set on the artificial heart drive system.

Percent Systole. The percentage of time during each complete cardiac cycle spent in ejection, as set on the artificial heart drive system.

Drive Pressure. The force in the drive lines used to eject blood from the ventricles during systole; the pressure is set on the

right and left sides of the artificial heart and is measured on the Utah Drive System II.

Derivative of Pressure/Derivative of time [(+) dP/dt max] - the maximal rate of left ventricular pressure development (Wallace, Sheldon & Mitchell, 1963). This value is obtained in the artificial heart by monitoring the left sided pressure line for the greatest change in pressure over time.

Summary

In the last 20 years 200 million dollars have been spent on the development of the artificial heart. At the University of Utah 400 sheep and calves have received artificial hearts in the last 15 years (DeVries, 1986). The artificial heart implanted most frequently is the Jarvik-7 (Symbion, Inc.). Development of the Jarvik-7 was a team effort that included input from 250 investigators (DeVries, 1986).

The theoretical framework which describes the effects of the artificial heart on contractility and the effect of contractibility, in turn, on thrombus formation has been discussed. The impact with which the blood components hit the walls of the Jarvik-7 leads to sub-lethal changes in red blood cells and changes in the shape of the platelets. If the impact with which the blood components hit the walls of the artificial heart can be decreased, the percentage of patients having a stroke can possibly be decreased.

CHAPTER III

METHODOLOGY

Introduction

The study examined the effect of three experimental parameters of the artificial heart on the rate of change in the rise of intraventricular pressure. The methods used to collect the data are described in this chapter.

Design

An experimental design was used to determine the effects of the most frequently used drive parameters on the rise of intraventricular pressure in the artificial heart. The independent variables that were manipulated included heart rate, percent systole, and left sided drive pressures. The dependent variable was the change in the rise of the ventricular pressure the (+) dP/dt max. The (+) dP/dt max was measured by the dP/dt program verson 2.1 on the COMDU software version 1.9.2.

Setting

The study was conducted in the Total Artificial Heart Laboratory at a southwestern medical menter. The mock circulation, using water, is connected to the Jarvik-7 (Figure 4). Each of the pressure chambers of the mock circulation is connected to a pressure module in a Hewlett Packard Monitor #78534A. The Jarvik-7 is controlled by the Utah Drive

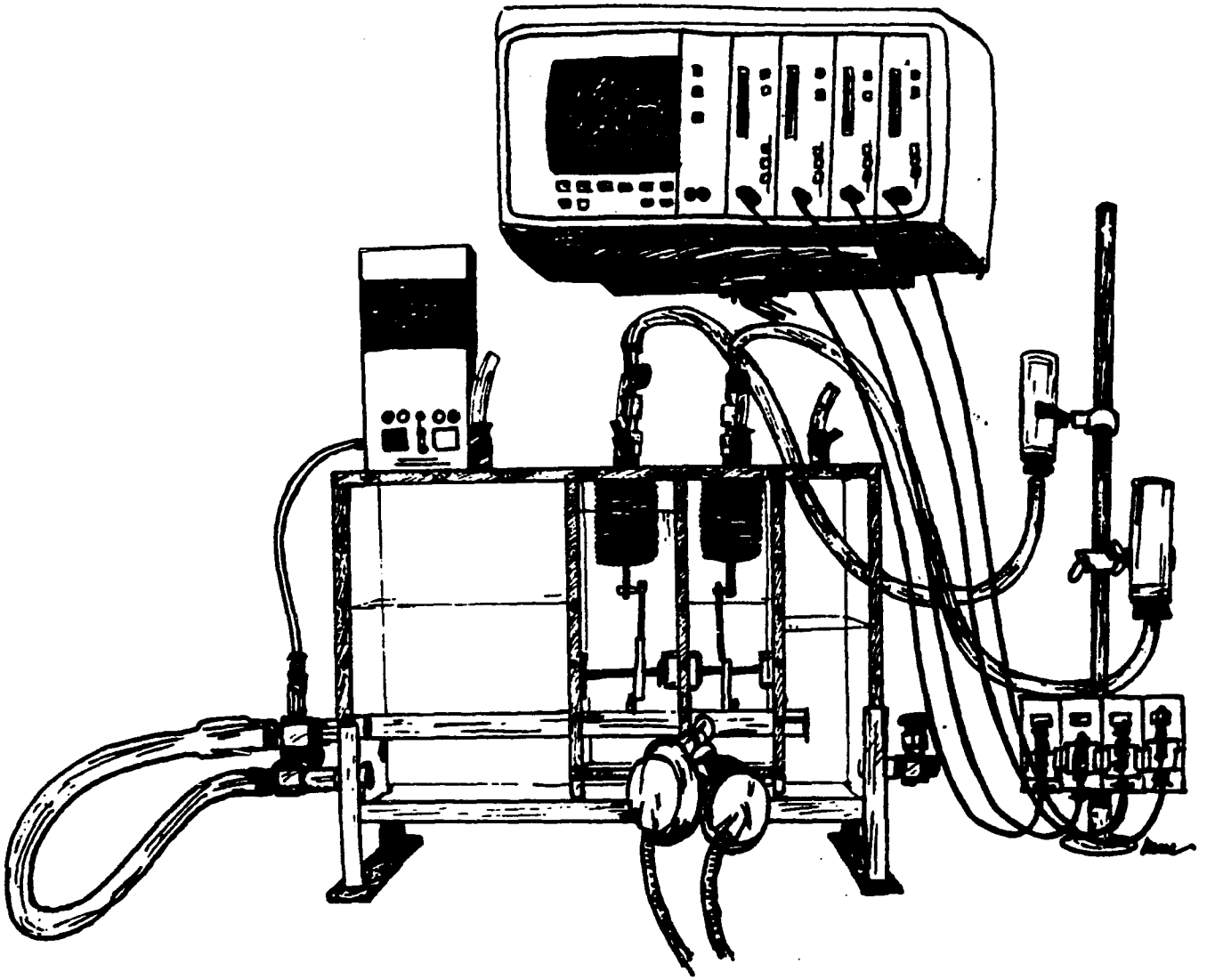

Figure 4. Mock circulation connected to Jarvik-7.

System (Figures 5 and 6). The monitoring system used to collect data is part of the COMDU system. A flow meter is attached to the mock circulation to monitor actual cardiac output. All equipment needed to collect the information is present in the laboratory (Figures 4-6).

Sample

No human subjects were involved in the study. The effects of changing the parameters of the artificial heart were observed on the mock circulation. Thus, the experimental parameters could be manipulated without detrimental effects to patients. Three experimental parameters were used to maintain waveforms that were physiologically capable of supporting the patient on the artificial heart. The parameters were heart rate, percent systole, and drive pressure.

Waveform Analysis

The waveforms for filling and for ejection met the same evaluation criteria applied to any patient with an artificial heart implant. During diastole the artificial heart fills. The device fills passively; as it fills the diaphragm is pushed down by the blood entering the ventricle. As the blood enters the ventricle the air underneath the diaphragm is pushed out of the artificial heart through the drivelines connected to the Utah Drive System II. The stroke volume of the heart can be calculated indirectly by measuring the volume of air that leaves through the drive lines. For each one cc of air that passes through the drivelines, one ml of blood enters the artificial heart (Mays et al., 1986).

HEART CONTROLLER

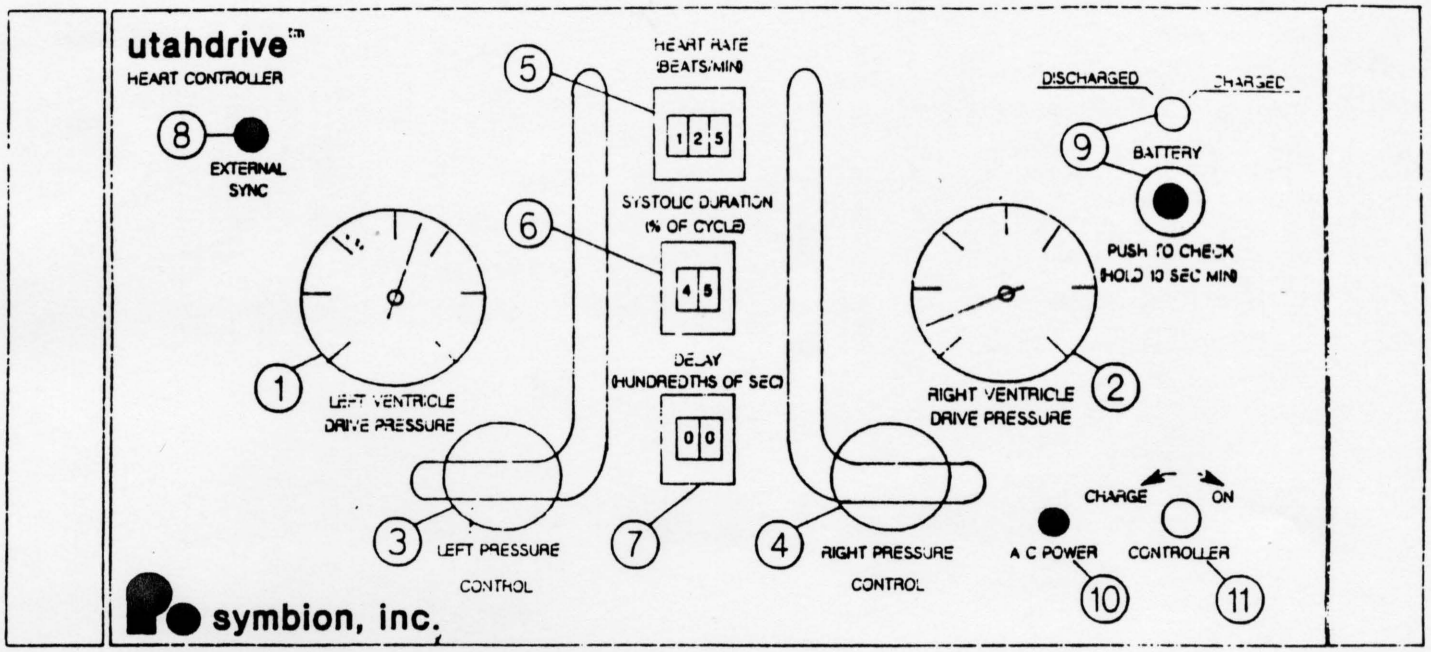

Figure 5. Heart Controller of Utah Drive System II.

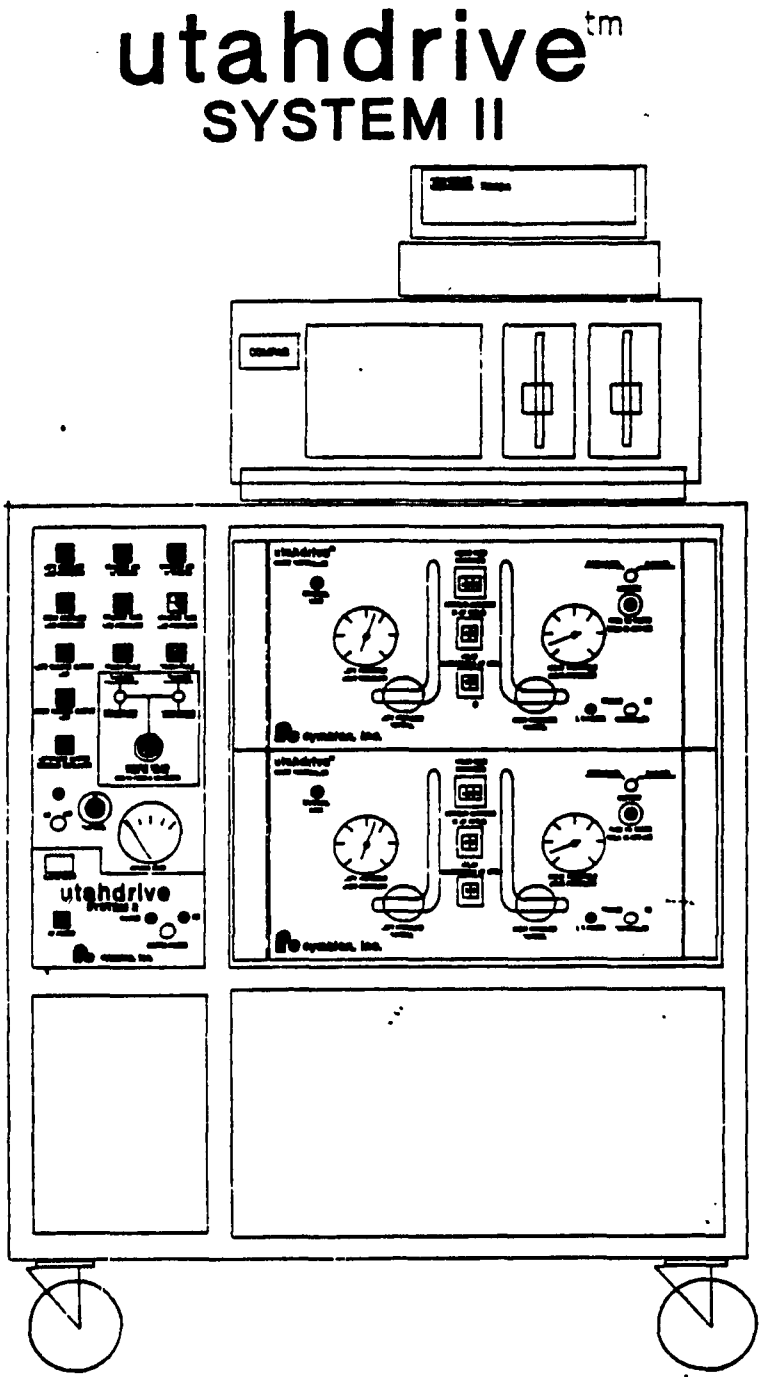

Figure 6. Utah Drive System II

The COMDU waveform, the label given to the filling graph, indicates the air flow out of the heart. The filling graph allows the COMDU program to assist in determining when blood starts to enter into the ventricle. The computer places a line that represents blood flowing into the heart (Figure 2, point A). The line indicates that blood flow into the ventricle has started.

During the diastolic phase of the cardiac cycle in the artificial heart, complete filling was not allowed to occur. Complete filling indicates that the flow of blood has stopped in the ventricle. The decreased flow state can predispose the patient to clot formation. An example of complete filling is seen in Figure 2. The key indicator that flow has stopped is when the graph on the COMDU tracing reaches the horizontal axis (Figure 2, point B). An example of normal filling is noted in Figure 3. In normal filling the graph does not meet the horizontal axis and flow never stops.

The systolic phase is monitored by viewing the drive pressure waveforms. The drive pressure waveforms represent an increase in air pressure underneath the diaphragm. Initially the air pressure increases until the pressure in the ventricle is greater than the pressure of the pulmonary artery or the aorta. When this point is reached (Figure 7, point C), blood is ejected from the ventricle. The plateau region on the drive pressure represents the ejection of blood. The left drive pressure waveform is much higher than the right because of the higher afterload in the systemic circulation.

The major principle in the systolic phase is to completely eject the blood from the ventricle. When complete ejection occurs, a higher

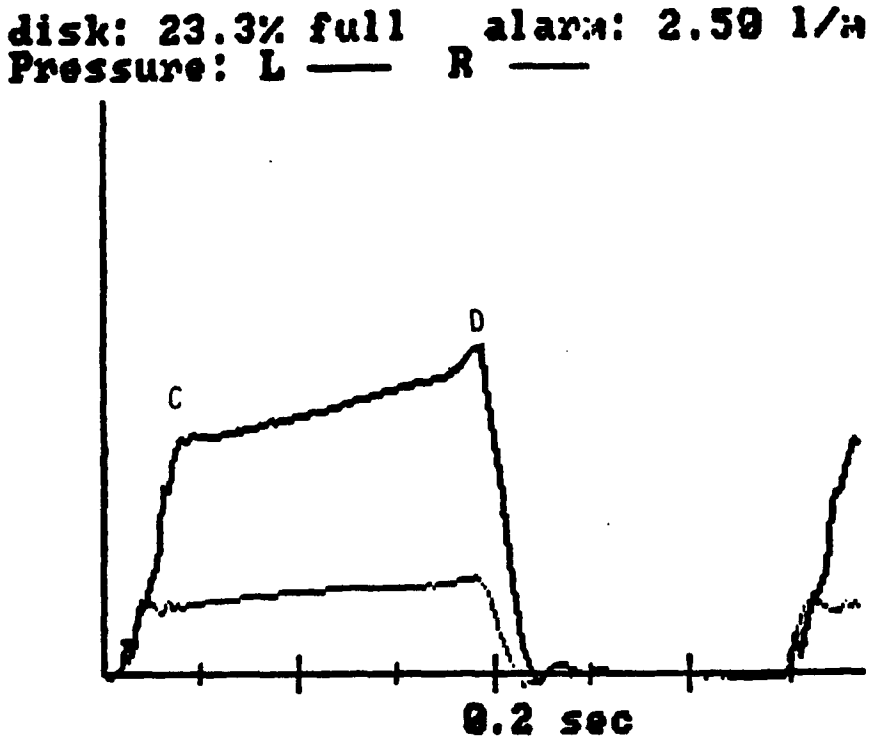

Figure 7. Drive Pressure Waveform indicating full ejection has occurred. Isovolumetric contraction in the waveform indicates increases in pressure underneath the diaphragm of the artificial heart without ejection of blood. Point C indicates where blood is starting to be ejected from the ventricle. Point D indicates the portion of the waveform that indicates full eject.

cardiac output is produced. Complete ejection can be identified by viewing a small upswing with a point at the end of the waveform (Figure 7, point D). The upswing with a point is considered to be reserve. Some reserve is necessary in systole to overcome an increase in afterload or to give the patient a higher cardiac output with an increase in preload. Examples of complete eject and partial eject are seen in Figures 7 and 8 respectively. In Figure 7 reserve is present and as much blood as possible is pumped out of the ventricle. In Figure 8 full ejection has not occurred. If the principles of partial fill and complete eject are not followed in patients there is an increased risk of thrombus formation due to the stasis of blood. For further information on manipulation of the drive parameters, refer to Appendix A.

Data Collection Procedure

The data collection procedure simulated a clinical situation as much as possible. Parameters were put in the mock circulation that mimicked pressures in the normal range for humans. For example, the left atrial pressure (LAP) on the mock circulation was kept between 8-16 mmHg. The blood pressure was kept between 110-140 mmHg systolic to simulate a patient's normal blood pressure.

To begin, the power source for the Utah Drive System II and the alarm system side of the panel were activated. The disk with the COMDU software was placed in drive A of the Compaq computer connected to the Utah Drive System II, and a blank disquette was inserted in

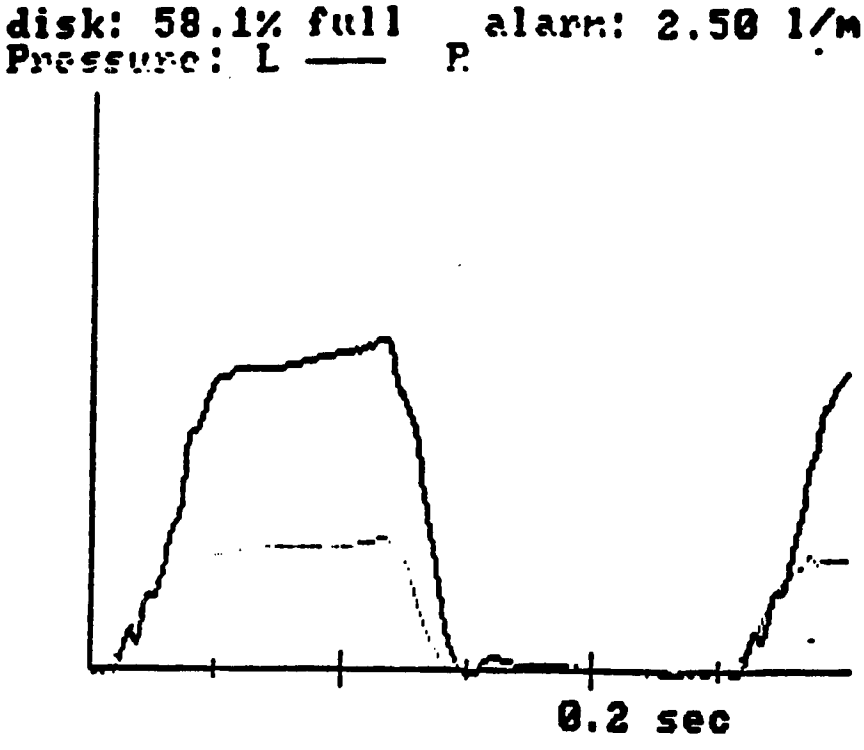

Figure 8. Drive Pressure Waveform, indicating lack of reserve; full ejection has not occurred.

drive B. The computer which allows the operator to monitor the COMDU waveform and the drive pressure waveforms was also activated.

Next, the pressure transducers on the mock circulation were zeroed and calibrated. The left atrial pressure and the systemic blood pressure were then set. The left atrial pressure was set between 8-16 mmHg and the systemic systolic blood pressure was set between 110-140 mmHg. To set these pressures, the resistance in the mock circulation was adjusted. The resistance, representing the systemic vascular resistance, was raised to 25 inches and the pulmonary vascular resistance was raised to 13 inches.

Once the parameters in the mock circulation were set, the experimental variables on the drive system were manipulated. The parameters were tested in random order. The data collection procedure used for the heart rate parameter was as follows. The heart rate was tested from 103 to 141 beats per minute in increments of two. When the heart rate was set at 103, the percent systole was manipulated with the drive pressure remaining constant at 150 mmHg. The percent systole was manipulated to attain a COMDU waveform and the drive pressure that exemplified partial fill and full eject. After satisfactory waveforms were obtained, the computer was directed from the COMDU program to the dP/dt program. The dP/dt program was accessed and an average of ten (+) dP/dt max values was recorded. Non-experimental extraneous variables were collected. Right atrial pressure, left atrial pressure, mean pulmonary artery pressure, systolic blood pressure, and diastolic blood pressure were collected from the Hewlett Packard monitor. The actual cardiac output was collected from a flow meter attached to the

mock circulation. When the heart rate was increased to 105, only percent systole was manipulated to obtain satisfactory COMDU and drive pressure waveforms. The heart rate was increased to 141 beats per minute and back to 103 beats per minute in increments of two beats per minute.

The procedure was repeated with the percent systole held constant and drive pressure was manipulated as the experimental variable. The heart rate was started at 103 beats per minute and increased by increments of two beats per minute and increased by increments of two beats per minute to 141 beats per minute then back to 103 beats per minute. The percent systole was kept constant at 58% and the drive pressure was manipulated to provide satisfactory COMDU and drive pressure waveforms. After the waveforms were determined to be satisfactory, the (+) dP/dt max and the nonexperimental variables were recorded. The percent systole setting was started at 54% and increased by increments of one to 61% then decreased by one back to 54%. The heart rate was varied while keeping the drive pressure constant at 150 mmHg. The COMDU and drive pressure waveforms were evaluated. After adjustments to the heart rate were made and the waveforms were determined to be satisfactory, the computer was directed to the dP/dt program and the (+) dP/dt max was collected. The nonexperimental parameters of left atrial pressure, right atrial pressure, systolic blood pressure, diastolic blood pressure, and mean pulmonary artery pressure were collected from the Hewlett Packard monitor. The actual cardiac output was collected from a flow meter attached to the mock circulation.

The procedure was repeated maintaining heart rate at 115 and varying the drive pressure. The percent systole was changed by increments of one from 45% to 62% and back to 45% by increments of one. The drive pressure was manipulated to obtain satisfactory COMDU and drive pressure. After evaluation of the waveforms, the (+) dP/dt max was collected and the nonexperimental variables were collected.

The data for drive pressure was collected in increments of three mmHg. The first group maintained the percent systole constant 58%. The manipulated experimental variable was heart rate. The drive pressure was increased from 142 mmHg to 166 mmHg then back to 142 mmHg. After each change in drive pressure, the heart rate was manipulated to attain satisfactory COMDU and drive pressure waveforms. After the waveforms were determined to be satisfactory, the (+) dP/dt max and nonexperimental variables were collected.

In the next group, the drive pressure was changed in increments of three mmHg from 130 mmHg to 193 mmHg and back to 130 mmHg. The heart rate was kept constant at 120. The percent systole was the manipulated experimental variable. After each change in drive pressure, the heart rate was manipulated to maintain satisfactory COMDU and drive pressure waveforms. When the waveforms were determined to be satisfactory, the (+) dP/dt max and the nonexperimental variables were collected (Refer to Table 1 for grouping of experimental variables).

The waveforms at each parameter were collected to record all the parameters used when obtaining the (+) dP/dt max. The (+) dP/dt max was read from the screen. The average of ten (+) dP/dt max values was recorded with each of the three parameters manipulated.

Table 1. Grouping of Experimental Variables

Group	Independent Variable	Uniformly Changed Variable	Constant Variable
1	Heart Rate	Percent Systole	Drive Pressure
2	Heart Rate	Drive Pressure	Percent Systole
3	Percent Systole	Drive Pressure	Heart Rate
4	Drive Pressure	Heart Rate	Percent Systole
5	Drive Pressure	Percent Systole	Heart Rate
6	Percent Systole	Heart Rate	Drive Pressure

Instruments

The instrument which measured (+) dP/dt max was the dP/dt program version 2.1 on the COMDU software version 1.9.2. The software enabled the operator to visualize, in a waveform, the rate of increase of the intraventricular pressure (Figure 9). The program takes ten waveforms and averages (+) dP/dt max for those ten waveforms. The operator could visualize the waveforms to see if the computer software was determining the appropriate point in the curve to calculate the (+) dP/dt max. The dP/dt program in the artificial heart does not actually measure the (+) dP/dt max of the blood in the ventricle in a patient. Instead it measures the rate at which air is raising the diaphragm in the ventricle. The COMDU software also enabled the investigator to monitor the waveforms to determine if the parameters were physiologically compatible. The software has been tested on animal models and has been reliable in clinical practice.

The nonexperimental variables of right atrial pressure, left atrial pressure, mean pulmonary artery pressure, systolic blood pressure, and diastolic blood pressure were collected from the Hewlett Packard monitor #78534A. The actual cardiac output was measured utilizing the flow meter attached to the mock circulation.

Data Analysis Plan

The hypotheses tested were as follows:

A change in heart rate will significantly affect the (+) dP/dt max.

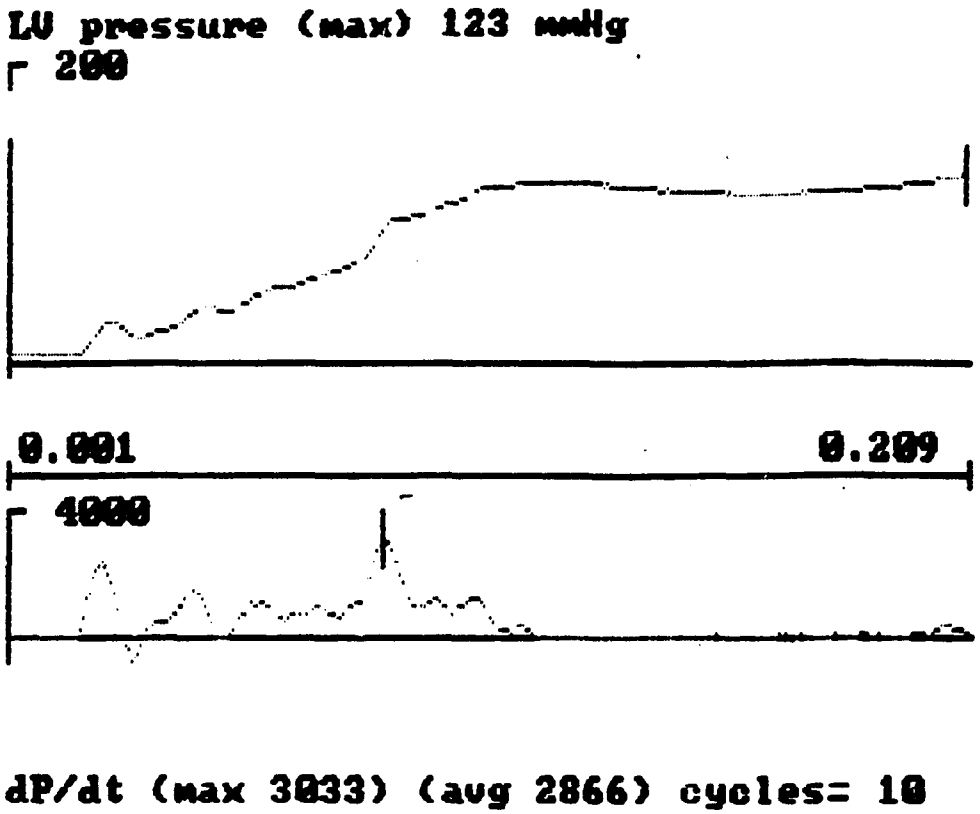

Figure 9. Rate of intraventricular pressure change. The top curve is the increase in pressure. The bottom curve measures the highest rate of intraventricular pressure change.

A change in percent systole will significantly affect the (+) dP/dt max.

A change in the drive pressure will significantly affect the (+) dP/dt max.

A multiple stepwise regression analysis was performed to ascertain the significant contributions of heart rate, percent systole and drive pressures on (+) dP/dt max. In step one of the stepwise regression, the uniformly changed variable was entered into the regression equation. The remaining variables were then entered into the regression equation on step two. In this way the variance due to the uniformly changed variable would be accounted for prior to entering the other variables. The significance level was set at $p < .05$. In addition, the correlation matrices were examined for multicollinearity among independent and nonexperimental variables.

Summary

The methodology for the data collection process involved creating six groups. In each group one of the experimental variables was uniformly increased by predetermined increments; one of the experimental variables was held constant, and one of the variables was used to manipulate the waveforms indicative of partial filling and complete ejection. The dependent variable and the nonexperimental variables were collected by utilizing the COMDU software, the Hewlett Packard monitor measuring the pressures in the mock circulation, and a flow meter attached to the mock circulation.

The data analysis performed was multiple stepwise regression analysis and Pearson correlation coefficients. The data analysis determined the contribution of each variable on the variance of the dependent variable, (+) dP/dt max.

CHAPTER IV

RESULTS

Chapter four presents the results of hypotheses testing. The method of data analysis utilized to test the three hypotheses was a stepwise multiple regression. In addition, the results of Pearson correlation coefficients among the variables are discussed in terms of multicollinearity.

Six groups were created for the data collection (refer to Table 1). In group one, heart rate, the independent variable, was manipulated to attain the desired COMDU and drive pressure waveforms. The percent systole was changed uniformly and the drive pressure was held constant.

In group two, heart rate, the independent variable, was manipulated to attain the desired COMDU and drive pressure waveforms. The drive pressure was changed uniformly and the percent systole was held constant.

In group three, percent systole, the independent variable, was manipulated to attain the desired COMDU and drive pressure waveforms. The drive pressure was uniformly changed and the heart rate was held constant.

In group four, drive pressure, the independent variable, was manipulated to attain the desired COMDU and drive pressure waveform. The heart rate was changed uniformly and the percent systole was held constant.

In group five, drive pressure, the independent variable, was manipulated to attain the desired COMDU and drive pressure waveforms. The percent systole was changed uniformly and the drive pressure was held constant.

In group six, percent systole, the independent variable, was manipulated to attain the desired COMDU and drive pressure waveforms. The heart rate changed uniformly and the drive pressure was held constant.

Descriptive Statistics

In group one there were 16 observations. The mean heart rate was 120.68 beats/minute with a standard deviation of 17.69 and a range of 105-154 beats/minute. The mean percent systole was 57.50 with a standard deviation of 2.36 and a range of 54-61. The mean right atrial pressure was 9.06 mmHg with a standard deviation of 0.25 and a range of 9-10 mmHg. The mean left atrial pressure was 15.12 mmHg with a standard deviation of 1.25 and a range of 14-17 mmHg. The mean systolic blood pressure was 120.62 mmHg with a standard deviation of 5.42 and a range of 114-126 mmHg. The mean diastolic blood pressure was 70.81 mmHg with a standard deviation of 2.45 and a range of 67-74 mmHg. The mean of the mean pulmonary artery pressure was 19.81 mmHg with a standard deviation of 1.22 with a range of 19-22 mmHg. The mean of the actual cardiac output is 5.29 L/minute with a standard deviation of 0.44 with a range of 4.45-5.69 L/minute. The mean (+) dP/dt max was 3405.93 with a standard deviation of 468.90 and a range of 2671-4013 (refer to Table 2).

Table 2. Descriptive Statistical Analysis of Group 1 (N=16)

Variable	Mean	Standard Deviation	Range
Heart Rate (beats/minute)	120.68	17.69	105-154
Percent Systole (%)	57.50	2.36	54-61
Right Atrial Pressure (mmHg)	9.06	0.25	9-10
Left Atrial Pressure (mmHg)	15.12	1.25	14-17
Systolic Blood Pressure (mmHg)	120.62	5.42	114-126
Diastolic Blood Pressure (mmHg)	70.81	2.45	67-74
Mean Pulmonary Artery Pressure (mmHg)	19.81	1.22	19-22
Actual Cardiac Output (L/min)	5.29	0.44	4.45-5.69
(+) dP/dt max	3405.93	468.90	2671-4013

In group two there were 18 observations. The mean heart rate was 130.44 beats/minute with a standard deviation of 19.57 and a range of 110-165 beats/minute. The mean drive pressure was 154.00 mmHg with a standard deviation of 7.97 and a range of 142-166 mmHg. The mean right atrial pressure was 10.00 mmHg with a standard deviation of 0.00. The mean left atrial pressure was 13.27 mmHg with a standard deviation of 0.46 and a range of 13-14 mmHg. The mean systolic blood pressure was 122.83 mmHg with a standard deviation of 2.62 and a range of 118-125 mmHg. The mean diastolic blood pressure was 69.83 mmHg with a standard deviation of 2.20 and a range of 67-74 mmHg. The mean of the mean pulmonary artery pressure was 17.22 mmHg with a standard deviation of 0.43 with a range of 17-18 mmHg. The mean of the actual cardiac output is 6.23 L/minute with a standard deviation of 0.35 with a range of 5.58-6.61 L/minute. The mean (+) dP/dt max was 3939.94 with a standard deviation of 108.68 and a range of 3693-4067 (refer to Table 3).

In group three there were 44 observations. The mean drive pressure was 161.50 mmHg with a standard deviation of 19.25 and a range of 130-193 mmHg. The mean percent systole was 54.36 with a standard deviation of 4.93 and a range of 47-62. The mean right atrial pressure was 10.00 mmHg with a standard deviation of 0.00. The mean left atrial pressure was 11.09 mmHg with a standard deviation of 2.11 and a range of 8-14 mmHg. The mean systolic blood pressure was 127.61 mmHg with a standard deviation of 5.92 and a range of 114-136 mmHg. The mean diastolic blood pressure was 69.36 mmHg with a standard deviation of 0.94 and a range of 67-71 mmHg. The mean of the mean pulmonary artery pressure was 15.77 mmHg with a standard deviation of 1.33 with a range

Table 3. Descriptive Statistical Analysis of Group 2 (N=18)

Variable	Mean	Standard Deviation	Range
Heart Rate (beats/minute)	130.44	19.57	110-165
Driving Pressure (mmHg)	154.00	7.97	142-166
Right Atrial Pressure (mmHg)	10.00	0.0	
Left Atrial Pressure (mmHg)	13.27	0.46	13-14
Systolic Blood Pressure (mmHg)	122.83	2.62	118-125
Diastolic Blood Pressure (mmHg)	69.83	2.20	67-74
Mean Pulmonary Artery Pressure (mmHg)	17.22	0.43	17-18
Actual Cardiac Output (L/minute)	6.23	0.35	5.58-6.61
(+) dP/dt max	3939.94	108.68	3693-4067

of 14-18 mmHg. The mean of the actual cardiac output is 6.58 L/minute with a standard deviation of 0.47 with a range of 5.28-6.97 L/minute. The mean (+) dP/dt max was 4308.41 with a standard deviation of 481.21 and a range of 3489-4937 (refer to Table 4).

In group four there were 40 observations. The mean heart rate was 121.55 with a standard deviation of 11.67 and a range of 103-141. The mean drive pressure was 149.75 mmHg with a standard deviation of 3.30 and a range of 147-158 mmHg. The mean right atrial pressure was 10.03 mmHg with a standard deviation of 0.16 and a range of 10-11 mmHg. The mean left atrial pressure was 13.55 mmHg with a standard deviation of 0.88 and a range of 13-16 mmHg. The mean systolic blood pressure was 123.30 mmHg with a standard deviation of 2.15 and a range of 119-126 mmHg. The mean diastolic blood pressure was 71.63 mmHg with a standard deviation of 2.84 and a range of 66-76 mmHg. The mean of the mean pulmonary artery pressure was 17.33 mmHg with a standard deviation of 0.66 with a range of 17-19 mmHg. The mean of the actual cardiac output is 6.32 L/minute with a standard deviation of 0.15 with a range of 6.03-6.59 L/minute. The mean (+) dP/dt max was 3835.98 with a standard deviation of 272.69 and a range of 3054-4179 (refer to Table 5).

In group five there were 36 observations. The mean drive pressure was 158.22 mmHg with a standard deviation of 28.26 and a range of 120-203 mmHg. The mean percent systole was 53.50 with a standard deviation of 5.26 and a range of 45-62. The mean right atrial pressure was 8.00 mmHg with a standard deviation of 0.00. The mean left atrial pressure was 11.75 mmHg with a standard deviation of 1.05 and a range of 9-13 mmHg. The mean systolic blood pressure was 123.64 mmHg with a standard

Table 4. Descriptive Statistical Analysis of Group 3 (N=44)

Variable	Mean	Standard Deviation	Range
Drive Pressure (mmHg)	161.50	19.25	130-193
Percent Systole (%)	54.36	4.93	47-62
Right Atrial Pressure (mmHg)	10.00	0.00	
Left Atrial Pressure (mmHg)	11.09	2.11	8-14
Systolic Blood Pressure (mmHg)	127.61	5.92	114-136
Diastolic Blood Pressure (mmHg)	69.36	0.94	67-71
Mean Pulmonary Artery Pressure (mmHg)	15.77	1.33	14-18
Actual Cardiac Output (L/minute)	6.58	0.47	5.28-6.97
(+) dP/dt max	4308.41	481.21	3489-4937

Table 5. Descriptive Statistical Analysis of Group 4 (N=40)

Variable	Mean	Standard Deviation	Range
Heart Rate (beats/minute)	121.55	11.67	103-141
Drive Pressure (mmHg)	149.75	3.30	147-158
Right Atrial Pressure (mmHg)	10.03	0.16	10-11
Left Atrial Pressure (mmHg)	13.55	0.88	13-16
Systolic Blood Pressure (mmHg)	123.30	2.15	119-126
Diastolic Blood Pressure (mmHg)	71.63	2.84	66-76
Mean Pulmonary Artery Pressure (mmHg)	17.33	0.66	17-19
Actual Cardiac Output (L/minute)	6.32	0.15	6.03-6.59
(+) dP/dt max	3835.98	272.69	3054-4179

deviation of 10.37 and a range of 108-136 mmHg. The mean diastolic blood pressure was 69.67 mmHg with a standard deviation of 0.83 and a range of 69-72 mmHg. The mean of the mean pulmonary artery pressure was 15.80 mmHg with a standard deviation of 0.75 with a range of 14-17 mmHg. The mean of the actual cardiac output is 5.53 L/minute with a standard deviation of 0.75 with a range of 4.32-6.52 L/minute. The mean (+) dP/dt max was 3779.42 with a standard deviation of 344.13 and a range of 3169-4544 (refer to Table 6).

In group six there were 39 observations. The mean heart rate was 122.49 beats/minute with a standard deviation of 11.41 and a range of 103-141 beats/minute. The mean percent systole was 58.26 with a standard deviation of 0.44 and a range of 58-59. The mean right atrial pressure was 10.00 mmHg with a standard deviation of 0.00. The mean left atrial pressure was 13.31 mmHg with a standard deviation of 0.61 and a range of 13-16 mmHg. The mean systolic blood pressure was 124.28 mmHg with a standard deviation of 2.46 and a range of 121-128 mmHg. The mean diastolic blood pressure was 71.49 mmHg with a standard deviation of 2.29 and a range of 67-75 mmHg. The mean of the mean pulmonary artery pressure was 17.18 mmHg with a standard deviation of 0.45 with a range of 17-19 mmHg. The mean of the actual cardiac output is 6.36 L/minute with a standard deviation of 0.13 with a range of 6.11-6.56 L/minute. The mean (+) dP/dt max was 3894.08 with a standard deviation of 526.72 and a range of 2645-4345 (refer to Table 7).

Table 6. Descriptive Statistical Analysis of Group 5 (N=36)

Variable	Mean	Standard Deviation	Range
Drive Pressure (mmHg)	158.22	28.26	120-203
Percent Systole (%)	53.50	5.26	45-62
Right Atrial Pressure (mmHg)	8.00	0.00	
Left Atrial Pressure (mmHg)	11.75	1.05	09-13
Systolic Blood Pressure (mmHg)	123.64	10.37	108-136
Diastolic Blood Pressure (mmHg)	69.67	0.83	69-72
Mean Pulmonary Artery Pressure (mmHg)	15.80	0.75	14-17
Actual Cardiac Output (L/minute)	5.53	0.75	4.32-6.52
(+) dP/dt max	3779.42	344.13	3169-4544

Table 7. Descriptive Statistical Analysis of Group 6 (N=39)

Variable	Mean	Standard Deviation	Range
Heart Rate (beats/minute)	122.49	11.41	103-141
Percent Systole (%)	58.26	0.44	58-59
Right Atrial Pressure (mmHg)	10.0	0.00	
Left Atrial Pressure (mmHg)	13.31	0.61	13-16
Systolic Blood Pressure (mmHg)	124.28	2.46	121-128
Diastolic Blood Pressure (mmHg)	71.49	2.29	67-75
Mean Pulmonary Artery Pressure (mmHg)	17.18	0.45	17-19
Actual Cardiac Output (L/minute)	6.36	0.13	6.11-6.56
(+) dP/dt max	3894.08	526.72	2645-4345

Hypothesis Testing

Hypothesis One

The first null hypothesis tested was: the heart rate will not significantly affect the (+) dP/dt max. In group one, the percent systole, the variable that was changed uniformly when heart rate was the independent variable, was entered on step one of a stepwise regression equation. The adjusted R square (R^2) for percent systole was .33 (F=8.28, p = .01). Thus, percent systole accounted for 33% of the variance prior to entering any other variables. Next, heart rate, right atrial pressure, left atrial pressure, systolic blood pressure, diastolic blood pressure, mean pulmonary arterial pressure, and actual cardiac output were entered on step two. The first variable that entered the regression equation on step two was left atrial pressure (adjusted R^2 = .92, F = 89.2, p = .00). Left atrial pressure accounted for an additional 56% of the variance in (+) dP/dt max. The only other variable that entered the regression equation on step two was actual cardiac output. The adjusted R^2 after actual cardiac output was entered into the equation was .95 (F = 112, p = .00). Heart rate, the independent variable did not enter into the regression equation, as it was not significant.

In group two, drive pressure, the variable that was changed uniformly when heart rate was the independent variable, was entered on step one of the stepwise regression analysis. The adjusted R^2 was .03 (F = 1.47, p = NS). Therefore drive pressure did not account for any significant variance when it was entered. On step two of the analysis, heart rate, right atrial pressure, left atrial pressure, mean pulmonary pressure, and actual cardiac were entered. The first variable that

entered the equation on step two was actual cardiac output. The adjusted R^2 was .71 (F = 21.4, p = .00). No other variables, including heart rate, entered the equation. (See Tables 8 and 9 for a summary of the results of testing hypothesis one.)

In summary, the first null hypothesis was tested with two different stepwise regression equations. Heart rate did not enter as a significant variable in any of the analyses, therefore the first null hypothesis could not be rejected.

Hypothesis Two

The second null hypothesis tested was: the percent systole will not significantly affect the (+) dP/dt max. In group three, the drive pressure, the variable that was changed uniformly when percent systole was the independent variable, was entered on step one of a stepwise regression equation. The adjusted R^2 for drive pressure was .96 (F=1060.4, p = .00). Thus, drive pressure accounted for 96% of the variance prior to entering any other variables. Next percent systole, right atrial pressure, left atrial pressure, systolic blood pressure, diastolic blood pressure, mean pulmonary artery pressure, and actual cardiac output were entered on step two. The first variable that entered the regression equation on step two was actual cardiac output (adjusted R^2 = .97, F = 605.5, p = .00). Actual cardiac output accounted for an additional 0.5% of the variance in (+) dP/dt max. The second variable that entered the regression equation on step two was mean pulmonary artery pressure (adjusted R^2 .98, F = 582.1, p = .00). Mean pulmonary artery pressure accounted for an additional 1% of the variance in (+) dP/dt max. The

Table 8. Stepwise Regression Analysis: Effects of Selected Variables on (+) dP/dt max, Group 1* (N=16)

Step	Variable	Beta	T	Adjust R^2	R^2 Change	F	Sig
1	Systole	.82	2.76	.33	.37	8.3	$p < .05$
2	LAP	-.64	-4.28	.92	.56	89.2	$p < .05$
3	ACO	.75	3.42	.96	.03	112.3	$p < .05$

* Heart Rate = independent variable
Drive Pressure = held constant
Percent Systole = uniformly changed

KEY

LAP - Left Atrial Pressure
Systole - Percent Systole
ACO - Actual Cardiac Output

Table 9. Stepwise Regression Analysis: Effects of Selected Variables on (+) dP/dt max, Group 2* (N=18)

Step	Variable	Beta	T	Adjust R^2	R^2 Change	F	Sig
1	DPres	1.35	4.55	.03	.08	1.47	p = NS
2	ACO	1.83	6.16	.71	.66	21.42	p < .05

* Heart Rate = independent variable
Percent Systole = held constant
Drive Pressure = uniformly changed

KEY

DPres - Left Drive Pressure
ACO - Actual Cardiac Output

third variable that entered the regression equation on step two was the diastolic blood pressure (adjusted R^2 = .98, F = 570.70, p = .00). Diastolic blood pressure accounted for an additional 0.5% of the variance in the (+) dP/dt max. The fourth variable that entered the regression equation on step two was the systolic blood pressure (adjusted R^2 = .98, F = 499.1, p = .00). Systolic blood pressure accounted for an additional 0.1% of the variance in the (+) dP/dt max. Percent systole did not enter the regression equation therefore it did not account for any of the significant variance on (+) dP/dt max.

In group six, heart rate, the variable that was changed uniformly when percent systole was the independent variable, was entered on step one of the stepwise regression analysis. The adjusted R^2 was -.01 (F = 0.6, p = .46). Therefore heart rate did not account for any of the significant variance when it was entered separately. On step two of the analysis, percent systole, right atrial pressure, left atrial pressure, mean pulmonary artery pressure, and actual cardiac output were entered. The first variable that entered the equation on step two was systolic blood pressure (adjusted R^2 = .11, F = 3.4, p = .04). Systolic blood pressure accounted for 10% of the variance in (+) dP/dt max. The second variable to enter into the regression equation on step two was actual cardiac output (adjusted R^2 .24, F = 5.00, p = .01). Actual cardiac output accounted for 13% of the variance in (+) dP/dt max. The percent systole did not enter the regression equation and therefore it did not account for any of the variance on (+) dP/dt max. (See Tables 10 and 11 for a summary of the results of testing of hypothesis two).

Table 10. Stepwise Regression Analysis: Effects of Selected Variables on (+) dP/dt max, Group 3* (N=44)

Step	Variable	Beta	T	Adjust R^2	R^2 Change	F	Sig
1	DPres	.51	5.17	.96	.96	1060.44	$p < .05$
2	ACO	.43	5.14	.97	.01	605.51	$p < .05$
2	XPAP	-.26	-4.69	.98	.01	582.15	$p < .05$
2	DBP	-.17	-4.27	.98	.01	570.70	$p < .05$
2	SBP	-.29	-2.13	.98	.00	499.10	$p < .05$

* Percent Systole = independent variable
Heart Rate = held constant
Drive Pressure = uniformly changed

KEY

DPres - Drive Pressure
SBP - Systolic Blood Pressure
ACO - Actual Cardiac Output
DBP - Diastolic Blood Pressure
XPAP - Mean Pulmonary Artery Pressure

Table 11. Stepwise Regression Analysis: Effects of Selected Variables on (+) dP/dt max, Group 6* (N=39)

Step	Variable	Beta	T	Adjust R^2	R^2 Change	F	Sig
1	HRate	2.72	3.42	-.01	.02	.57	p = NS
2	SBP	2.22	2.89	.11	.14	3.42	p < .05
2	ACO	.56	2.65	.24	.14	4.99	p < .05

* Percent Systole = independent variable
Drive Pressure = held constant
Heart Rate = uniformly changed

KEY

HRate - Heart Rate
SBP - Systolic Blood Pressure
ACO - Actual Cardiac Output

In summary, the second null hypothesis was tested with two different stepwise regression equations. Percent systole did not enter as a significant variable in either of the analyses; therefore the second null hypothesis could not be rejected.

Hypothesis Three

The third null hypothesis tested was: the drive pressure will not significantly affect the (+) dP/dt max. In group four, the heart rate, the variable that was changed uniformly when drive pressure was the independent variable was entered on step one of a stepwise regression equation. The adjusted R^2 for heart rate was .03 ($F = 2.3$, $p = NS$). Thus, heart rate did not account for any significant variance in the (+) dP/dt max. Next drive pressure, right atrial pressure, left atrial pressure, systolic blood pressure, diastolic blood pressure, mean pulmonary artery pressure, and actual cardiac output were entered on step two. The first variable that entered the regression equation on step two was mean pulmonary artery pressure (adjusted $R^2 = .75$, $F = 60.4$, $p = .00$). Mean pulmonary artery pressure accounted for an additional 72% of the variance in (+) dP/dt max. The second variable that entered the regression equation on step two was actual cardiac output (adjusted $R^2 = .86$, $F = 78.9$, $p = .00$). Actual cardiac output accounted for an additional 11% of the variance in (+) dP/dt max. The third variable that entered the regression equation on step two was diastolic blood pressure (adjusted $R^2 = .87$, $F = 67.3$, $p = .00$). Diastolic blood pressure accounted for an additional 1% of the variance in (+) dP/dt max. Drive pressure did not enter into the regression, therefore the drive pressure does not account any significant variance in the (+) dP/dt max.

In group five, the percent systole, the variable that was changed uniformly, when drive pressure was the independent variable, was entered on step one of a stepwise regression equation. The adjusted R^2 for percent systole was .25 ($F = 12.7$, $p = .00$). Therefore the percent systole accounted for 25% of the variance in the (+) dP/dt max. Next drive pressure, right atrial pressure, left atrial pressure, systolic blood pressure, diastolic blood pressure, mean pulmonary arterial pressure, and actual cardiac output were entered on step two. The first variable that entered the regression equation on step two was actual cardiac output (adjusted $R^2 = .36$, $F = 11.0$, $p = .00$). Actual cardiac output accounted for an additional 11% of the variance in (+) dP/dt max. The second variable that entered the regression equation on step two was left atrial pressure (adjusted $R^2 = .63$, $F = 5.00$, $p = .00$). Left atrial pressure accounted for an additional 27% of the variance in (+) dP/dt max. The third variable that entered the regression equation on step two was drive pressure (adjusted $R^2 = .67$, $F = 19.1$, $p = .00$). Drive pressure accounted for an additional 4% of the variance in (+) dP/dt max. The drive pressure was only 4% accountable for the variance in the (+) dP/dt max. (See Tables 12 and 13 for a summary of the results of testing of hypothesis two.)

In summary, the third null hypothesis was tested with two different stepwise regression equations. Drive pressure accounted for 4% of the variance in (+) dP/dt max. The percent of variance, although small, was significant, therefore the null hypothesis was accepted.

Table 12. Stepwise Regression Analysis: Effects of Selected Variables on (+) dP/dt max, Group 4* (N=40)

Step	Variable	Beta	T	Adjust R^2	R^2 Change	F	Sig
1	HRate	.09	.41	.03	.06	2.33	p = NS
2	XPAP	-.53	-3.98	.75	.71	60.49	p < .05
2	ACO	.85	6.03	.86	.10	78.87	p < .05
2	DBP	.47	2.28	.87	.02	67.33	p < .05

* Drive Pressure = independent variable
Percent Systole = held constant
Heart Rate = uniformly changed

KEY

HRate - Heart Rate
ACO - Actual Cardiac Output
DBP - Diastolic Blood Pressure
XPAP - Mean Pulmonary Artery Pressure

Table 13. Stepwise Regression Analysis: Effects of Selected Variables on (+) dP/dt max, Group 5* (N=36)

Step	Variable	Beta	T	Adjust R^2	R^2 Change	F	Sig
1	Systol	.49	.84	.25	.27	12.69	$p < .05$
2	ACO	2.08	6.13	.36	.13	10.97	$p < .05$
2	LAP	-.63	-4.72	.63	.26	20.47	$p < .05$
2	DPres	-1.34	-2.41	.67	.05	19.12	$p < .05$

* Drive Pressure = independent variable
Heart Rate = held constant
Percent Systole = uniformly changed

KEY

DPres - Left Drive Pressure
LAP - Left Atrial Pressure
Systol - Percent Systole
ACO - Actual Cardiac Output

Correlations Among Variables

The correlation matrices were then inspected for multicollinearity or redundency. A correlation coefficient of 0.70 or greater indicates the independent variables are highly correlated and may be measuring the same thing. When variables are highly correlated, one variable may need to be eliminated if the two variables cannot be combined in a theoretically relevant way.

Evaluation of the correlation matrices indicated that many of the variables were highly correlated. For example, in group one the correlation between heart rate and systole was $r = .93$, and between actual cardiac output and systolic blood pressure, $r = .98$. Table 14 shows the correlations indicating redundency for group one. Therefore, some of the variables that entered the regression equation in group one were measuring the same thing.

In group two the correlations between drive pressure and heart rate was $r = .97$, between heart rate and actual cardiac output was $r = -.97$ and between drive pressure and actual cardiac output is $-.897$. Nonexperimental variables that were highly correlated included systolic blood pressure and actual cardiac output $r = .88$, and diastolic blood pressure and mean pulmonary artery pressure, $r = -.71$. Table 15 contains the correlation matrix for group two.

An example of a high correlation in group three was between percent systole and drive pressure, $r = -.99$. Correlations between nonexperimental variables that were multicollinear were between left atrial pressure and mean pulmonary artery pressure, $r = .96$, and between systolic

Table 14. Pearson Correlations Between Independent and Extraneous Variables for Group 1* Indicating Multicollinearity** (N=16)

	Heart Rate	Percent Systole	RAP	LAP	SBP	DBP	XPAP	ACO
Heart Rate	1.00	.93			-.99	.92	-.72	-.98
Percent Systole		1.00		-.72	.94	.94	-.82	-.88
RAP			1.00					
LAP				1.00			.84	
SBP					1.00	-.91	.71	.98
DBP						1.00	-.83	-.86
XPAP							1.00	.62
ACO								1.00

* Heart Rate = independent variable
Drive Pressure = held constant
Percent Systole = uniformly changed

** r = .70 or greater

Table 15. Pearson Correlations Between Independent and Extraneous Variables for Group 2* Indicating Multicollinearity** (N=18)

	Heart Rate	Drive Pressure	RAP	LAP	SBP	DBP	XPAP	ACO
Heart Rate	1.00	.97			-.80	.78		-.97
Drive Pres.		1.00				.85	-.75	-.90
RAP			1.00					
LAP				1.00				
SBP					1.00			.88
DBP						1.00	-.71	
XPAP							1.00	
ACO								1.00

* Heart Rate = independent variable
Percent Systole = held constant
Drive Pressure = uniformly changed

** r = .70 or greater

blood pressure and the actual cardiac output, r = .94. Table 16 contains the variables which were highly correlated for group three.

In group four high correlations were between diastolic blood pressure and heart rate, r = .95, between actual cardiac output and systolic blood pressure, r = .87, and between systolic blood pressure and heart rate, r = -.92. Table 17 contains the variables which were highly correlated for group four.

The high correlations in group five were between actual cardiac output and drive pressure, r = .95, between percent systole and actual cardiac output, r = -.94. The nonexperimental variables that had high correlations were between actual cardiac output and systolic blood pressure, r = .98, and between the left atrial pressure and the mean pulmonary artery pressure, r = .81. Table 18 contains the variables which were highly correlated for group five.

The high correlations in group six were between heart rate and diastolic blood pressure, r = .99, and between heart rate and systolic blood pressure, r = -.98. The nonexperimental parameters that highly correlated were between diastolic blood pressure and systolic blood pressure, r = -.97 and between systolic blood pressure and actual cardiac, r = .72. Table 19 contains the variables which were highly correlated in group six.

Summary

Six groups were utilized for the data analysis. In each group, one of the independent experimental variables heart rate, percent systole,

Table 16. Pearson Correlations Between Independent and Extraneous Variables for Group 3* Indicating Multicollinearity** (N=44)

	Drive Pres	Percent Systol	RAP	LAB	SBP	DBP	XPAP	ACO
Drive Pres	1.00	-.99		-.95	.95	-.83	-.90	.85
Percent Systole		1.00		.97	-.95	.82	.92	-.84
RAP			1.00					
LAP				1.00	-.86	.84	.96	-.70
SBP					1.00	-.79	-.81	.94
DBP						1.00	.81	
XPAP							1.00	
ACO								1.00

* Percent Systole = independent variable
Heart Rate = held constant
Drive Pressure = uniformly changed

** r = .70 or greater

Table 17. Pearson Correlations Between Independent and Extraneous Variables for Group 4* Indicating Multicollinearity** (N=40)

	Heart Rate	Drive Pres.	RAP	LAP	SBP	DBP	XPAP	ACO
Heart Rate	1.00				-.92	.95		-.77
Drive Pres		1.00						
RAP			1.00					
LAP				1.00		-.72	.89	
SBP					1.00	-.90		.87
DBP						1.00	-.74	-.72
XPAP							1.00	
ACO								1.00

* Drive Pressure = independent variable
Percent Systole = held constant
Heart Rate = uniformly changed

** r = .70 or greater

Table 18. Pearson Correlations Between Independent and Extraneous Variables for Group 5* Indicating Multicollinearity** (N=36)

	Drive Pres	Percent Systole	RAP	LAP	SBP	DBP	XPAP	ACO
Drive Pres	1.00	-.98			.98			.95
Percent Systole		1.00			-.97			-.94
RAP			1.00					
LAP				1.00			.81	
SBP					1.00			.98
DBP						1.00		
XPAP							1.00	
ACO								1.00

* Drive Pressure = independent variable
Heart Rate = held constant
Percent Systole = uniformly changed

** r = .70 or greater

Table 19. Pearson Correlations Between Independent and Extraneous Variables for Group 6* Indicating Multicollinearity** (N=39)

	Heart Rate	Percent Systole	RAP	LAP	SBP	DBP	XPAP	ACO
Heart Rate	1.00				-.98	.99		-.74
Percent Systole		1.00						
RAP			1.00					
LAP				1.00			.75	
SBP					1.00	-.97		.72
DBP						1.00		
XPAP							1.00	
ACO								1.00

* Percent Systole = independent variable
Drive Pressure = held constant
Heart Rate = uniformly changed

** r = .70 or greater

or drive pressure, was manipulated to test its effect on the dependent variable, (+) dP/dt max.

Hypothesis testing was performed with a stepwise multiple regression. Only one of the three null hypothesis tested were accepted due to the lack of significant variance accounted for by the experimental variables. Drive pressure accounted for 4% of the variance in (+) dP/dt max when hypothesis three was tested.

Pearson correlations were obtained to inspect for multicollinearity. The correlations indicated that many of the variables were highly correlated and could be measuring the same thing. The multicollinearity problem also decreased the predictive abilities in the stepwise multiple regression.

CHAPTER V

CONCLUSIONS AND DISCUSSION

Introduction

The last chapter discusses the conclusions based on the result obtained from the data analysis. Possible explanation of the results are also discussed. The limitations of the study are outlined and implications for nursing research and clinical practice are highlighted.

Conclusions

Three null hypotheses were tested. First, a change in heart rate will not significantly affect the (+) dP/dt max. Second, a change in the percent systole will not significantly affect the (+) dP/dt max. Third, a change in drive pressure will not significantly affect the (+) dP/dt max. A mock circulation connected to a total artificial heart was used to collect data to test the hypothesis. Data were analyzed with a stepwise multiple regression analysis and Pearson correlation coefficients.

Results of data analysis indicated that two of the null hypotheses could not be rejected. The effects of heart rate and percent systole on the dependent variable (+) dP/dt max were not significant. Heart rate did not account for any significant variance in the (+) dP/dt max when it was entered into the regression equation as the independent variable. The percent systole did not account for any significant variance

in the (+) dP/dt max in the two groups in which percent systole was the independent variable.

The drive pressure accounted for 4% of the variance in the (+) dP/dt max in one of the two groups in which it was entered into the equation in step two. In the second group, drive pressure did not enter the regression equation. Thus, drive pressure was statistically significant in one group and only accounted for a small amount of variance. The small amount was not clinically significant.

The effects of the experimental variables did not appear to be accounting for any significant variance that occurred in the (+) dP/dt max. However, the correlations of the nonexperimental variables created multicollinearity, making it difficult to evaluate the effects of the experimental variables. The correlations seem especially high between the nonexperimental variables which represent preload. These variables are left atrial pressure, and mean pulmonary artery pressure. When testing hypothesis one, left atrial pressure accounted for 56% of the variance in (+) dP/dt max. When testing hypothesis three, mean pulmonary artery pressure accounted for 72% of the variance in (+) dP/dt max. In hypothesis one, percent systole was changed uniformly while varying heart rate. In hypothesis three heart rate was changed uniformly while varying drive pressure. Thus, as indicated in the literature, preload was the major determinant of (+) dP/dt max.

When examining the mechanisms of the normal human heart the preload has the greatest effect on the (+) dP/dt max (Cohn, 1985). As the preload increases, the muscle fibers in the heart increase in length. When the

contraction of these muscle fibers occurs the rate of pressure rise is increased due to the increased contractility of the heart muscle.

In the artificial heart it is also apparent that an increase in preload will increase the (+) dP/dt max. The variables that most significantly affected the (+) dP/dt max were mean pulmonary artery pressure, and left atrial pressure, all are indicators of preload.

Heart rate did not account for any significant variance in (+) dP/dt max. When the intact heart rate is slowed, the amount of filling of the ventricle increases, increasing initial fiber stretch, thereby increasing the preload. However, changes in heart rates of 30 to 40 beats per minute are needed to influence fiber length, as stroke volume changes with small changes in heart rate to maintain a constant cardiac output. Preload did not increase with the mock circulation because of the small incremental changes made on the artificial heart, i.e., two beats per minute.

Limitations

The study was conducted in a laboratory situation with a mock circulation. Thus, the responses obtained may not adequately represent true physiologic pressures or cover the range of responses observed in patients. The mock circulation uses water instead of blood, which also decreases the generalizability of the findings to humans. Because of the high viscosity of blood, the physiologic pressures in the mock circulation may differ and also the affect on the dependent variable, (+) dP/dt max, may be altered because of the resistance that occurs with a more viscous liquid in the circulation.

Second, guidelines for interpretation of physiologically compatible waveforms are subjective. The guidelines used on patients are continually changing as more is learned about the total artificial heart. In the second patient who had an artificial heart implanted, the artificial heart parameters were managed by occasional full fill with the heart rate at low rates. Currently in patients the artificial heart is maintained at a faster rate with no occasional full fill during the diastolic phase.

Third, multicollinearity also was a problem. Many of the variables had high intercorrelations. The high intercorrelations of the nonexperimental variables decreased the confidence in the R squares ability to determine the variance of (+) dP/dt max.

Last, the sample size was small. One group included a sample of 16. A minimum of 5-10 sets of parameters per variable are needed for adequate statistical testing of the hypotheses. In the group with sample size of 16, the waveform analysis criteria prevented expanding the sample.

Implications for Nursing Practice

In critical care units nurses manage the technical aspects of the care. Thus nursing practice eventually will include manipulation of parameters when monitoring patients with artificial devices. Devices presently in use, such as the intra aortic balloon pump, were initially managed by the physician. Nursing became responsible for the timing of the balloon pump because of the immediate changes that needed to be made to respond to a change in the patient's condition. Nursing staff

are at the bedside 24 hours which enables the nurse to make changes in timing when needed.

Other mechanical assist devices are being developed which are less difficult to monitor. Improvements in such devices will require less technical training for nurses caring for patients who need mechanical assistance. Therefore, the use of mechanical assist devices is expected to increase. The rapid escalation in the use of devices will increase the educational needs for nurses who are challenged when caring for patients on mechanical assist devices.

Implications for Nursing Research

Future research with the mock circulation may be done on a variety of different assist devices. The range of assist devices include intra aortic balloon pumps, non-pulsatile ventricular assist devices, pulsatile ventricular devices, and the artificial heart. The assist devices can be compared in terms of (+) dP/dt max and also for their effect on the hemolysis of erythrocytes and damage to platelets. As nurses expand their knowledge base about the mechanical assist devices, they will be able to perform more sophisticated assessments. For example, in an artificial heart patient if the (+) dP/dt max is reduced, the problems with platelet damage are diminished. In a patient with a ventricular assist device with a high (+) dP/dt max, the platelet damage may be higher. Such knowledge will allow the health care team to anticipate potential patient problems.

Laboratory research needs to be replicated clinically with patients as subjects. The laboratory model that was utilized for this research

has its limitations and needs to be replicated on a model that has similar responses to those of a patient. When studies are conducted on animal and human models, the results can be compared to the mock circulation. The mock circulation can then be evaluated as a laboratory model. Second, the ability to generalize from the mock circulation to patients can then be evaluated.

Summary

The aim of the research was to investigate the effects of three parameters of the artificial heart on the (+) dP/dt max. The study was conducted using a mock circulation which was connected to an artificial heart. The data were collected using the COMDU software developed for the computer which monitors the artificial heart.

Stepwise regression analysis was utilized to test the three hypotheses. Two of the null hypotheses for the study could not be rejected, as the independent variable did not significantly affect (+) dP/dt max. Although the third hypothesis was accepted, the results were not clinically significant. Limitations in the study were multicollinearity among the independent variables, small sample size, and the inability of the mock circulation to represent human responses.

APPENDIX A

DESCRIPTION OF CLINICAL MANIPULATION OF THE DRIVE PARAMETERS

The Utah Drive System II controls the artificial heart. Parameters on the drive system that can be varied are right and left drive pressure (Figure 6), percent systole, heart rate and vacuum. The Utah drive system also has various monitoring capabilities. The Compaq computer at the top of the drive system is capable of measuring filling volumes, cardiac output, drive pressures, and (+) dP/dt max. Other capabilities include visualizing the COMDU waveforms for filling, and drive pressure waveforms for full eject.

The parameters of the artificial heart are interdependent. For example, if more filling is needed to improve the cardiac output, two interventions can be utilized. The first is to decrease the percent systole, which enables a longer period of time for filling to occur, therefore increasing the cardiac output. The decrease in systolic time indicates that a higher drive pressure is required to eject the blood in the shorter systolic time period. The second intervention is to decrease the heart rate to promote filling or increase the heart rate to promote filling or increase the heart rate to increase cardiac output. If the heart rate is increased, the diastolic and systolic time are both shortened. The drive pressure will then need to be increased to fully eject the blood from the ventricle or an additional manipulation of the percent systole can be made.

REFERENCES

Akutso, T. (1975). Artificial Heart: Total Replacement and Partial Support. Tokyo: Igaku Shoin Ltd.

Atsumi, K., Fujimasa, I., Imachi, K., Nishisaka, T., Mano, I., Ohmichi, H., Iwai, N., Miyake, H. & Kuono, A. (1979). Experimental results on long term survivals (over one month) with a total artificial heart. In Unger, F. (Ed.), Assisted Circulation, Berlin: Springer-Verlag.

Cohen, P. F. (1985). Clinical Cardiovascular Physiology. Philadelphia: W. B. Saunders.

DeVries, W. C. (1986). Techniques of using the mechanical heart. In Hurst, J. W. (Ed.), The Heart (pp. 2069-2076). New York: McGraw-Hill.

Guyton, A. C. (1986). Medical Physiology. Philadelphia: W. B. Saunders.

Hardwick, R. A., Hellums, J. D., Peterson, D. M., Moake, J. & Olson, J. (1981). Effects of PGI2 and Di-Butryl Cyclic-AMP on platelets exposed to shear stress. Transcripts of the American Society for Artificial Internal Organs. 27:192-197.

Henker, R., Shaffer & Whittaker, A. (1985). Ethics associated with the artificial heart. Pulse, 24(14), pp. 3-4.

Hung, T. C., Hochmath, R. M., Joist, J. H. & Sutera, S. P. (1976). Shear induced aggregatio and lysis of platelets. Transactions of the American Society for Artficial Internal Organs, 22, 285-288.

Jarvik, R. K., Smith, S. M., Lawson, J. H., Sandquist, G. M., Fukumasu, H., Olsen, D. B., Iwaya, F. & Kolff, W. J. (1978). Comparison of pneumatic and electrically powered total artificial hearts in vivo. Transcripts of the American Society for Artificial Internal Organs, 24:593-599.

Jarvik, R. K., Kessler, T. R., McGill, L. D., Olsen, D. B., DeVries, W. C., Deneris, J., Blaylock, J. T. & Kolff, W. J. (1981). Determinants of pannus formation in long-surviving artificial heart calves, and its prevention. Transactions of the American Society of Artificial Internal Organs, 27:90-94.

Johnston, G. G., Marzec, U. & Bernstein, E. F. (1975). Effects of surface injury and shear stress on platelet aggregation and serotonin release. Transactions of the American Society of Artificial Internal Organs, 21:413-421.

Kilgo, G. R., Toole, J. F. & McGhee, T. B. (1986). Cerebrovascular disease and neurological manifestations of heart disease. In Hurst, J. W. (Ed.), The Heart (pp. 1354-1364). New York: McGraw-Hill.

Lambert, J. & Naumann, A. (1979). Hemolysis in artificial heart valves due to high level, short duration laminar shear stress. In F. Unger (Ed.), Assisted Circulation (pp. 533-540). Berlin: Springer-Verlag.

Levinson, M. M., Smith, R. G., Cork, R. C., Gallo, J., Emery, R. W., Icenogle, T. B., Ott, R. A., Burns, G. L. & Copeland, J. G. (1986a). Thromboembolic complications of the Jarvik-7 total artificial heart: Case report. Artificial Organs, 10:236-244.

Levinson, M. M., Smith, R. G., Gallo, J., Cork, R., Emery, R. W., Icenogle, T., Ott, R. A. & Copeland, J. G. (1986b). Clinical problems facing recipients of total artificial hearts as bridge to cardiac transplantation: Results in two recent patients. In Andrade, E. D., Brophy, J. J., Detmar, D. E., et al. (Eds.), Artificial Organs: W. J. Kolff Festscrift. New York: VCH Publishers.

Levinson, M. M., Copeland, J. G., Smith, R. G., Cork, R. C., DeVries, W. C., Mays, J. B., Griffith, B. P., Kormos, R., Joyce, L. D., Pritzker, M. R., Semb, B. K. H., Koul, B., Menkis, A. H. & Keon, W. J. (1986c). Indexes of hemolysis in human recipients of the Jarvik-7 total artificial heart: A cooperative report of fifteen patients. The Journal of Heart Transplantation, 5:236-248.

Mays, J. B., Williams, M. A., Barker, L. E., Hastings, L. & DeVries, W. C. (1986). Diagnostic monitoring and drive system management of patients with total artificial heart. Heart & Lung, 15:466-475.

Oiknine, C. (1983). Rheology of the human blood. In D. N. Ghista (Ed.), Cardiovascular Engineering Part I: Modelling, (pp. 1-25). New York: Karger.

Olsen, D. B. (1979). The total artificial heart - a research tool or potential clinical reality. In Unger, F. (Ed.), Assisted Circulation. Berlin: Springer-Verlag.

Quaal, S. (1984). Comprehensive Intra-Aortic Balloon Pumping. St. Louis: C. V. Mosby.

_____ (1985). The artificial heart. Heart & Lung, 14:317-327.

Schroeder, M. A. (1986). Critique of the analysis of data in nursing research. In L. F. Fraelich Phillips (Ed.), A Clinician's Guide to the Critique and Utilization of Nursing Research. Norwalk, CT: Appleton-Century-Crofts.

Wallace, A. G., Skinner, S. & Mitchell, J. H. (1963). Hemodynamic determinants of the maximal rate of rise of left ventricular pressure. American Journal of Physiology, 205:30-36.

Willshaw, P., Nielsen, S. D., Nanas, J. Pichel, R. H. & Olsen, D. B. (1984). A cardiac output monitor and diagnostic unit for pneumatically driven artificial hearts. Artificial Organs, 8(2):215-219.

Zumbro, G. L., Shearer, G., Fishback, M. E. & Galloway, R. F. (1978). A prospective evaluation of the pulsatile assist device. The Annals of Thoracic Surgery, 28:269-272.