

DESIGN AND CONSTRUCTION OF A MOCK HUMAN CIRCULATORY SYSTEM

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INTRODUCTION

Congestive heart failure (CHF) contributes to more than 300,000 deaths every year in the United States [1]. CHF is a condition that causes the heart to inadequately distribute blood to the rest of the body, resulting in heart failure, poor perfusion, and ultimately, multi-system organ failure. Approximately 70,000 patients may benefit from a heart transplant, however, with only 2000 hearts available, patients must seek other alternatives [1]. Patients can improve their quality of life with support from a left ventricular assist device (LVAD). In order to comply with current FDA requirements, prior to *in vivo* testing in animal models, there must be a way to test LVADs and assure a functioning, reliable assist device *in vitro*, in an experimental flow loop. Models for circulation are becoming more popular and set the standard for testing pumps while varying hemodynamic parameters. Circulatory loop models must accurately represent important parameters in the human circulatory system under dynamic conditions. The American Society for Artificial Internal Organs (ASAIO) and the Society of Thoracic Surgeons (STS) suggest variables to be accounted for in a circulatory model [2]. Required testing also includes worst-case physiologic conditions. The purpose of this paper is to describe the construction of a mock circulatory loop and explain results obtained from preliminary *in vitro* testing with a centrifugal flow pump.

MOCK CIRCULATORY LOOP MODEL

The volume of the loop contains 5-6 liters of fluid. The systemic vascular resistance is inherently accounted for within the 1.5 inch schedule 40 polyvinyl chloride piping that is used for the majority of the loop between major components such as peripheral vessels, the heart, and the aorta. Additional resistance is added with 1.5 inch gate valves. Arterial and venous compliance are considered in the loop by using 1.5 inch inner diameter chambers, 16 inches tall, containing a certain height of water and a volume of air. A bladder with one-way valves simulates left ventricular contractions when 60 psi air is supplied as pulses. The one-way valves mimic the aortic and mitral valves. Flow rates are measured using in-line, ½ inch, infrared flow

meters. Differential pressure sensors are used to measure dynamic right atrial pressure, aortic pressure, and left atrial pressure. These sensors have negligible effects on the flow path. The diagram below shows the mock loop in greater detail and indicates the locations of the pressure sensors and flow meters.

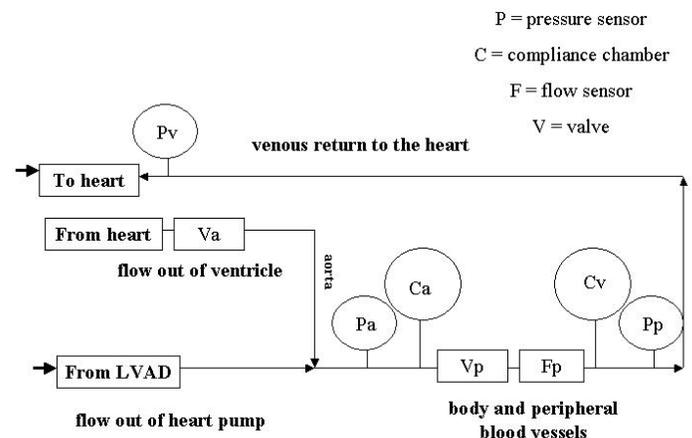


Figure 1. Mock Circulatory Loop Block Diagram

EXPERIMENTAL METHODS

Varying the following can change hemodynamic parameters: heart rate, % heart cycle in systole, ventricular pressure, aortic resistance, peripheral resistance, and pump rotational speed. Table 1 shows three of the variable hemodynamic conditions for a healthy and CHF patient. Values for heart rate and resistance reflect physiological changes in the body, secondary to CHF and exercise [3]. The loop must first prove to be accurate in describing the human physiologic conditions without an assist device. The CHF conditions were then tested again with an assist device to prove that there is an improvement in flow and pressure conditions, physiologically, suggesting improved organ and tissue perfusion [3].

Physiologic Condition	%heart cycle systole	Heart Rate (BPM)	% heart cycle in systole	% valve closed (R_{aortic})	% valve closed ($P_{peripheral}$)
Healthy Rest	45	60	45	0	.0020
Healthy Exercise	45	120	60	0	0
CHF Rest	35	60-80	25-35	.0020	.0045

Table 1. Physiologic Conditions

Healthy patients generally have a cardiac output of 5-6 liters per minute, an aortic pressure of 90-140 mmHg, and a peripheral resistance of 0.85 mmHg-s/mL [4]. Conversely, CHF patients suffer from heart failure and reduced output. Without a left ventricular assist device, they generally have a CO of 2-4 LPM, generally decreased aortic pressures compared to healthy subjects, and an increased peripheral resistance of 1.2-1.4 mmHg-s/mL [4].

RESULTS

Results obtained from the mock loop indicate comparable changes for pressure and flow rates. These values do correlate to expected values occurring in humans. Experimental results for the healthy patient are an average cardiac output of 4.9 liters per minute, aortic pressure of 98 mmHg, and a peripheral resistance of 0.84 mmHg-s/mL. Figure 2 illustrates results for the CHF condition without the assist of the centrifugal flow pump. Cardiac output is approximately 4.1 liters per minute, aortic pressure of 88 mmHg, and a resistance value of 1.2 mmHg-s/mL without an LVAD.

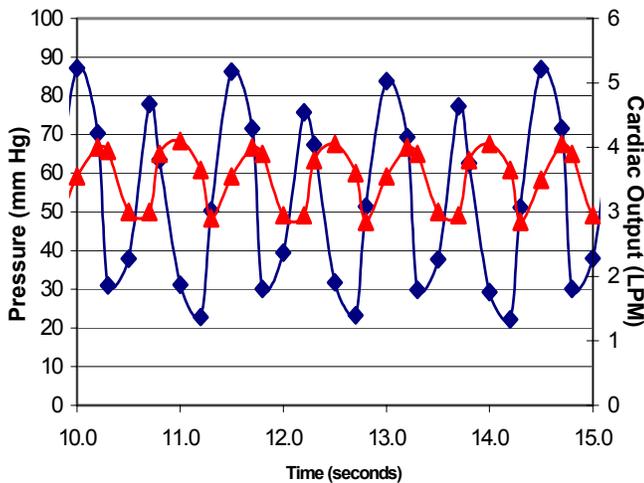


Figure 2. Aortic Pressure and Cardiac Output for CHF Patient without LVAD

After the insertion of a left ventricular assist device into the loop, there is a marked improvement in the cardiac output and aortic pressure, as seen in Figure 3. Cardiac output is increased to 6.1 liters per minute and the aortic pressure has increased to a maximum value of 128 mmHg.

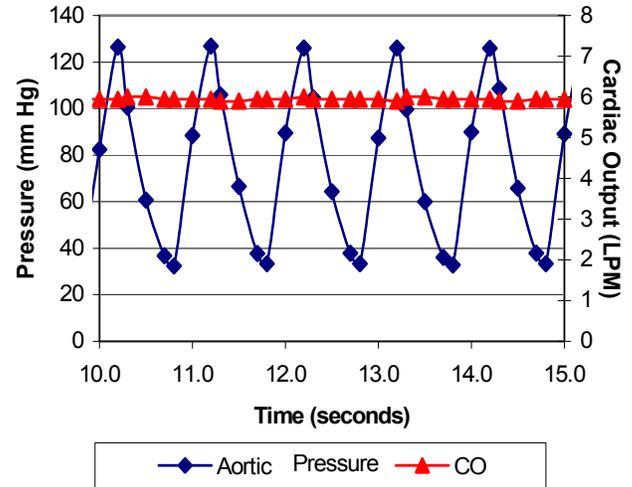


Figure 3. Aortic Pressure and Cardiac Output for CHF Patient with LVAD

DISCUSSION

The mock circulatory loop accurately represents various human physiologic conditions ranging from a healthy patient without an assist device to a CHF patient requiring an LVAD. Oscillations are evident secondary to the beating of the ventricle in the loop. However, once the LVAD is added to the system, the cardiac output increases and there are reduced oscillations, because flow through the loop is now continuous. While the aortic pressure and cardiac output are important parameters to measure, there are other variable and measurable parameters such as atrial pressures and vessel compliance. Future work would involve measuring the compliance as it varies with water height and air volume. Further testing would involve mimicking decreased compliance, which is the physiologic vessel response to CHF. Other testing would also include an alternative method to controlling resistance in the piping and the use of more pressure sensors to accurately measure the right and left atrial pressures. Most importantly, this loop can be used to test other types of pumps including an axial flow pump. Despite the need for improvement on this mock human circulatory loop, these preliminary results indicate that this loop is an appropriate tool for further *in vitro* testing of LVADs.

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