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A Novel Dynamic Cardiac Simulator Utilizing Pneumatic Artificial Muscle

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Abstract—**With the development of methods and skills of minimally invasive surgeries, equipments for doctors' training and practicing are in high demands. Especially for the cardiovascular surgeries, operators are requested to be familiar with the surgical environment of a beating heart. In this paper, we present a new dynamic cardiac simulator utilizing pneumatic artificial muscle to realize heartbeat. It's an artificial left ventricular of which the inner chamber is made of thermoplastic elastomers (TPE) with an anatomical structure of the real human heart. It is covered by another layer of material forming the artificial muscle which actuates the systole and diastole uniformly and omnidirectionally as the cardiac muscle does. Preliminary experiments were conducted to evaluate the performance of the simulator. The results indicated that the pressure at the terminal of the aorta could be controlled within the range of normal human systolic pressure, which quantitatively validated the new actuating mode of the heart-beating is effective.**

I. Introduction

There are 17 million people die of cardiovascular disease every year, accounts for about a third of the global death toll. High accuracy, complex anatomy and limited operating time leave the cardiovascular surgeries among those most difficult surgeries. Also, it's uneasy to train the cardio interventionists for the high risk of perforation leading to death of patients. In face of the challenges and insistent demands, researchers and doctors have done many researches to improve the function and quality of the surgical equipments. Among those apparatus that can simulate a surgical platform for operators practice surgical tools and estimate their performances, the dynamic cardiac simulator that can replicate physiological beating heart condition is one of the most complicated simulator system. An immense challenge is to simulate the myocardial contraction and relaxation leading to ventricular systole and diastole.

During the last decade, many researchers have been devoted to the development of a lifelike dynamic cardiac simulator, some representative simulators can be listed as following:

In 2004, academic medical center in the Netherlands produced a realistic 3-D gated cardiac phantom with known left ventricular volumes and ejection fractions to evaluate quantitative measurements obtained from gated myocardial single-photon emission computed tomography (SPECT). The system included a 3-D left ventricular (LV), a motor-driver cam drived a piston back and forth in order to vary LV volume [1]. The system controls the pressure difference in the blood circulation to drive the contraction and relaxation of the silicone ventricular wall. This driving way is on the contrary of the physiological principle of heartbeat which should be using systole and diastole motion to lead the blood flow.

Nagoya University in Japan built an in vitro patient-specific vascular model for simulating endovascular intervention in 2005[2]. This system provides a valuable platform for demonstrating human blood circulation system. However the system mainly focuses on the human aorta structure simulation; it does not have a dynamic heart structure to simulate the systole and diastole of a beating heart.

North Carolina State University developed a dynamically pressurized heart simulator in 2009, which could be used to control pressure and flow rate profiles in intact porcine hearts in order to quantify mitral regurgitation and evaluate the quality of mitral valve repair [3]. The expanded hearts used in the proposed system are dead porcine hearts which lack of myocardial contractile function. And the system uses a computer-controlled positive displacement pump to direct the flow of saline. The pressure of the saline flow causes physical deformation of the ventricular wall of the dead pork hearts. In this way, the pressure in the left ventricular is low during systole and high during diastole, which is on the contrary of the pressure condition in real human hearts' left ventricular during the contracting and relaxing processes. Therefore the environment the system presented is different with the real human beating heart. Besides, the application of dead pork hearts import restrictions on the application condition.

The Physics Department in Federal University of Sergipe developed a dynamic cardiac phantom for use in nuclear medicine [4]. It uses the similar actuating way with North Carolina State University's simulator which has an inverse pressure state with real human heart in the left ventricular cavity during systole and diastole. Instead of dead pork hearts, it makes an artificial ventricular with latex as the phantom that does not have an anatomic structure.

In 2010, a Canadian company, Shelley Medical Imaging Technologies, developed a dynamic multi-modality anthropomorphic heart phantom. The dynamic human heart replica is made of a hydrogen material that realistically

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mimics the biomechanical properties of human soft tissue and incorporates anatomically correct left and right ventricle structures for imaging under ultrasound, CT, X-ray and MRI [5]. The contraction and relaxation of left ventricular wall are unidirectional along the axis of heart which does not accord with the physiological principal.

Also in the same year 2010, Leeds University developed a device, which functioned as an artificial muscle wrap that assisted the failing heart by applying compressive force, leading to an improved output for the diseased heart [6]. This system builds a heart simulator using spring steel strips to produce the systole and diastole simulation. It uses software to simulate the blood circulation. It provides a new thought to drive the systole and diastole motion of the ventricular. However, it doesn't have the motions of systole and diastole involving the uniform contraction and relaxation of the ventricular wall.

The heart simulators mentioned above use either liquid pressure in the ventricular actuating the systole and diastole or mechanical driving way to create a simulated cardiovascular surgical environment. However, a real dynamic heart environment should contain the uniform contraction and relaxation movement of the myocardium and a structure with functional one-way valves. A novel driving mode should be designed to imitate the real beating heart more closely.

This article developed a novel dynamic heart simulator that utilized a pneumatic artificial muscle to realize the heartbeat. As for the actuating mode of the contraction and relaxation of the artificial muscle, the new heart simulator used an anatomy structure (pericardial cavity) in left ventricular as a gasbag into where the air was injected. The structure was considered as an artificial pneumatic muscle that could actuate the heartbeat. The design of the actuating mode was demonstrated in section II. The heart simulator's material and the structure details were illustrated in section III. We conducted a preliminary experiment to test the designed simulator. Results showed the new dynamic heart simulator could eject a normal stroke volume of a healthy people and provide a blood pressure within the normal range of a real heart.

II. The Pneumatic Artificial Muscle Actuating Mode Design

Medically, heart systole and diastole are motivated by $Ca2+$ ions causing myocardial contraction[7]. Since the myocardial is distributed in the left ventricular wall evenly, the motions of systole and diastole are uniformly and omnidirectionally[8]. With the function of the one-way valves in left ventricular, blood is injected into and the ejected out off the left ventricular cavity.

With purpose of simulating this systole and diastole processes realistically, we put forward a new actuating mode to simulate the motion of systole and diastole more like the real human heart.

In order to meet the requirements proposed above, this design used the following elements:

- **Actuation with the Artificial Muscle**

  The simulator uses the left ventricular wall as an artificial pneumatic muscle to simulate the contraction and relaxation of the myocardium. The pressure deference between the two sides of the left ventricular wall is used as the stimulation that causes the contraction and relaxation of the artificial muscle. Considering the pericardial cavity of the artificial left ventricular not only a simple anatomical structure but also an air cavity that could be used as a actuating source to change the pressure deference between the left ventricular and pericardial cavity.

- **A Valve Structure**

  The design uses an artificial valve to simulate the process of heartbeat. We add hard ribs in the valve to make sure the valve could function as a one-way valve that conformed to the principles of medical science and biology.

- **Separated Circuits**

  This system separates the actuating circuit and the blood circuit. The two different circuits could be tested and controlled separately. Thus the data that collected from the simulator would reflect the function much clear. Furthermore, the separated circuits design can reduce the volume of the system and facilities the miniaturization of the heart simulator.

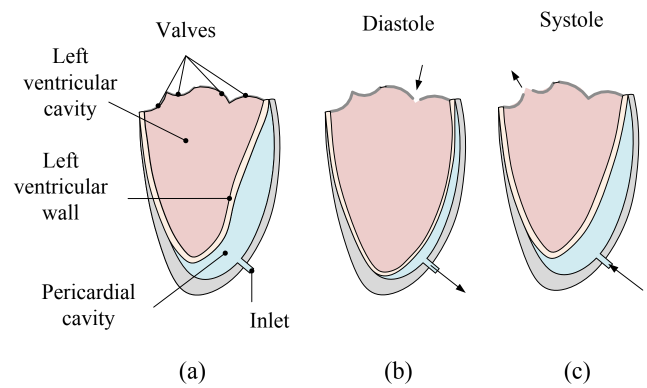

Figure 1: The designed air-pressure actuating mode

The designed actuating mode is shown in figure 1. As is illustrated, when air in the pericardial is exhausted out, pressure in the pericardial became lower than the pressure in the left ventricular. Relaxation is generated then by the pressure difference. The relaxation continues until the pressure between the two sides of the left ventricular wall is balanced. This period corresponds to the diastole of human heart. During this period, the blood comes into the left ventricular through the open gate of valve while the tricuspid valve is closed tight.

The systole period is demonstrated in left of figure 2. On the contrary to the diastole, the tricuspid valve is the open gate that allows the blood liquid to eject out of the left ventricular. The ejection is the result of the air injection that increases the pressure in the pericardial cavity. When the pressure deference is high enough to push the blood liquid out of the left ventricular, the valve opens towards to the outside of the left ventricular, allowing the liquid to flow into the aorta.

Thus the left ventricular accomplishes a circle period of injecting and ejecting blood.

III. THE DYNAMIC CARDIAC SIMULATOR

We chose thermoplastic elastomer (TPE) as the material of the artificial simulator. TPE is a combination of copolymers or a physical mix of polymers which consist of materials with both thermoplastic and elastomeric properties. TPE is widely used for medical products such as catheters where nylon block copolymers offered a range of softness ideal for patients [9]. The superelasticity of TPE makes it the perfect material for a heart simulator. Besides, in order to make the material act much more like the real organism, the contents of dibasic and diisocyanate were adjusted according to the classical data. The stiffness (also known as Yong's modulus) of heart muscle is 10–20kPa at the beginning of diastole, and 200–500kPa at the end of diastole [10~14].

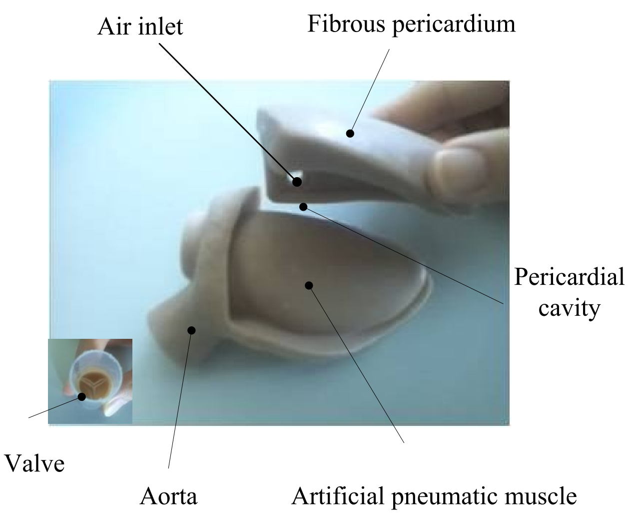

Figure 1: The artificial left ventricular simulator

As is demonstrated in figure 1, the model has five anatomical structure parts, the fibrous pericardium, the left ventricular, the pericardial cavity (the space between the left ventricular wall and fibrous pericardium), the valve and a part of the aorta. An air inlet on the fibrous pericardium is connected to the pericardial cavity by one side and the pressure source by the other side.

Water is used in the system to simulate the blood that flows in the blood circulation. Water in the tank is injected into the left ventricular through the pulmonary and ejected into the aorta trough the valve. The artificial pneumatic muscle in the figure is the left ventricular wall that carried on the movement of systole and diastole.

The left ventricular showed in the above picture is connected to the fibrous pericardium by adhesives on the surface of the fibrous pericardium's margin space. It contains an appropriate amount of adhesives that can enclose the space between the left ventricular wall and the fibrous pericardium, and also guarantees that there is enough space where the anatomical structure of the pericardial cavity (also the actuating air cavity) is.

IV. EXPERIMENTAL SETUP AND RESULTS

A. The test experiment

In order to test the dynamic cardiac simulator utilizing the new actuating mode, a preliminary experiment was performed.

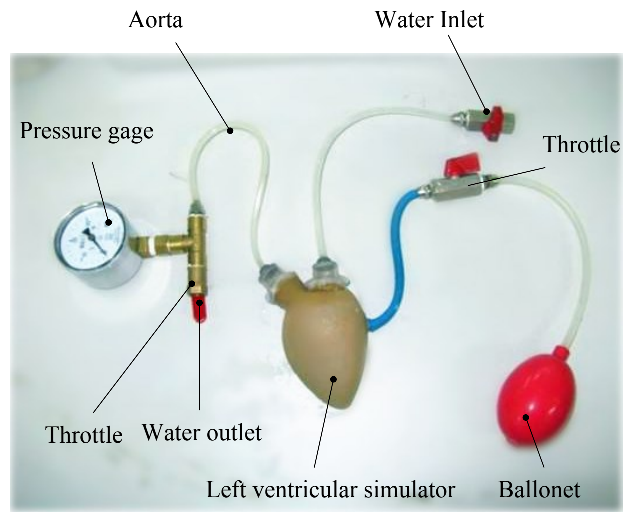

Figure 3: The test experiment

The assembled artificial left ventricular simulator that is prepared to be tested is shown in figure 3. There is a ballonet used as an actuating source to blow air into or inhale air out of the pericardial cavity.

The two tubes that connected to a water tank (which is not shown in figure 3.) are a part of the blood circulation. There was a pressure gage in the ejecting way of the blood circuit to record the pressure of the ejected water. Besides, two throttles were in the air circuit and blood circuit respectively to change the pressure in the two circuits.

Operator pressed the red air ballonet in the frequency of the normal human heart rate which was 80times/s. Then the air pressure in the pericardial cavity started to make the left ventricular systole and diastole as a real human heart. Water was injected into the left ventricular and ejected out of the left ventricular through the valve.

The operator set the experiment into six units, at each unit the operator pressed the ballonet ten times as the heart rate, recorded the pressure of the pressure gaga each time.

B. Results

The average pressure in the terminal of the aorta of each unit during each systole is illustrated in figure 4. The average ejecting pressure of the six units is 14.83kPa.

The normal human systolic pressure range for a healthy adult men (younger than 60 years old) is 90mmHg~120mmHg (11.97kPa~15.96kPa) [15, 16].

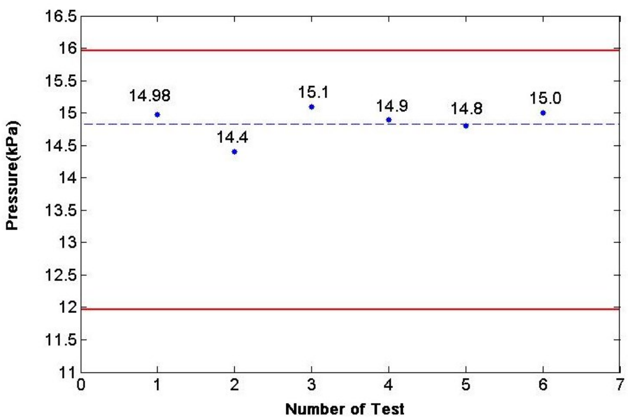

Figure 4: Rsultes of the preliminary examination.The range between the two red line represents the normal human systolic pressure in aorta. The blue points represents the average pressure data in the terminal aorta of the six texts. The blue dotted line represents the average pressure of the six tests's data.

The stroke volume during each pump was recorded by a measuring cylinder. The average stroke volume of the phantom was 65mL. It is close to a healthy adult's stroke volume which is 70mL.

V. CONCLUSION

A novel dynamic cardiac simulator with a real anatomical structure utilizing artificial pneumatic muscle was designed. A preliminary experiment was conducted to text the function of the left ventricular with the new actuating mode. The results of the experiment showed that the novel dynamic heart simulator could eject liquid out of the left ventricular without obvious backflow. In addition, the pressure data represented that the ejecting pressure during systolic period was in the range of normal human blood pressure. Therefore, it proved that the artificial pneumatic muscle could perform as designed and the valve was functional during the systole. The separated driving circuit and blood circuit could maintain the integrated process of blood circulation as the same way as systole and diastole of human heart.

In future work, a computer controlled pneumatic circuit will be added in the simulator. Furthermore, in order to control the amount of injecting air and the pressure in the artificial muscle, pressure and flow sensors will be added into the simulator. Thus the amount of stroke volume can be adjusted.

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