In Vitro Test of an Adaptive Flow Controller for a Continuous Flow LVAD

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Abstract

An adaptive flow controller designed in [1] for a magnetically levitated continuous flow (CF) left ventricular assist device (LVAD) was implemented on a real-time prototype controller board and put in a mock human circulatory loop for an in vitro test. Test results showed that the designed controller maintained the key hemodynamic variable of a congestive heart failure (CHF) patient within the normal physiologic range in either specified rest or exercise conditions. The transient response is slow and need improvement.

Key words: Adaptive controller, human circulation system, left ventricular assist device, mock circulation loop

I Introduction

A long-term left ventricular assist device (LVAD) relies on a physiologic controller to provide the desirable blood flow for the recipient in different physiologic conditions, which may occur in long period. The performance of the controller is often evaluated in terms of total peripheral flow, aortic pressure, left ventricular end-diastolic pressure.[2] Positive pump flow is also preferred to prevent blood recirculation and minimize power consumption. An adaptive flow controller for a magnetically levitated long term left ventricular assist device (LVAD) was designed in [1]. The controller used the pump head and the motor speed as the feedback signals, which are all reliable in long period. The pump head was derived from the axial displacement of impeller measured by the built-in Hall sensors in the pump housing. Computer simulation of this controller with the circulation model showed that the desired objectives were achieved.[1] In this paper, we present recent in vitro test results of this adaptive controller in a mock circulation loop.

II Experiment set up

A mock human circulation loop was used as an in vitro test rig for different versions of LVADs. The loop structure is shown in Fig 1. Two cardiac simulators were used to simulate pulsatile functions of the left and right ventricles. A semi-ellipsoidal shaped silicon diaphragm with 200ml capacity encased inside a transparent sealed air chamber formed the fluid chamber of the cardiac simulator. The air pressure inside the air chamber was pulsatile and controlled by a pneumatic control box (Utah Heart Controller, Symbion, Inc., Salt Lake City, UT). This pneumatic control box supplied driving (pressurized) and vacuum air alternately to the air chamber of cardiac simulators to simulate the systole and diastole phases of the natural heart. This pneumatic control box allows the desired variation of heart rate, the pressurized air pressure, the vacuum pressure, and the systole vs. diastole ratio. The compliance of systemic artery, systemic vein and pulmonary circulation was simulated by air-tight chambers with desired amount of air sealed at the top [3]. The variation in the total peripheral resistance (TPR) and the pulmonary resistance were implemented by a tuning clamp and a ball valve respectively, which allowed for a wide range adjustment. Water was used in this loop as the media. This loop was shown to be able to simulate the hemodynamic response of human circulation in different pathologic states and activities [3].

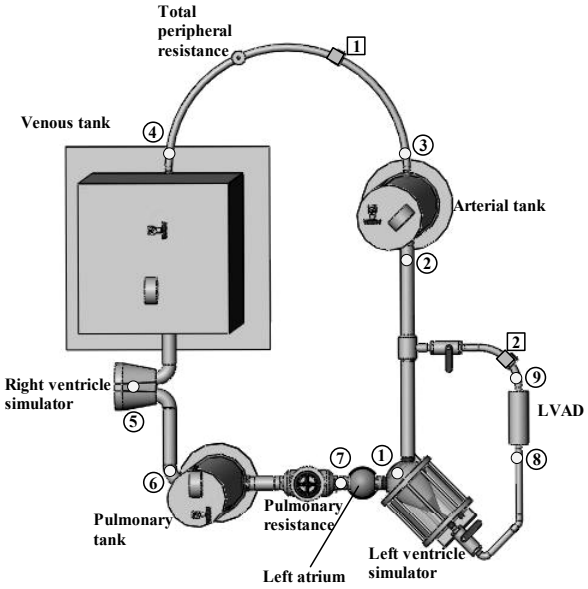

Figure 1. The mock human circulation loop (dots with number in circle: pressure sensors, diamond with number in square: ultrasonic flow sensors)

The total peripheral flow (1) and pump flow (2) were measured by ultrasonic flow meters (T110, Transonic system, NY). Pressure was measured by pressure sensors (PX26-DV005, Omega Inc., Stamford, CT). The LVAD was positioned between the left ventricle and the aorta, exactly where it will be placed in implantation surgery. A small centrifugal pump (MY2, Speck Pump Inc., FL) was used in this paper instead of a true LVAD for the initial

vitro testing of the designed physiologic controller. The rotational speed of pump was measured by an optical encoder (HEDS, US Digital Co., Vancouver, WA). The pump head used in the control algorithm of [1] was obtained from the difference between the inlet pressure and outlet pressure of the pump. The control algorithm was implemented on a real-time prototype controller board (DS1104, dSPACE Inc., MI) to adjust the speed of MY2 pump. All data were sampled at 200Hz and low-pass filtered at 60Hz by the real-time controller board, and processed in Matlab (Mathworks, Inc., Natick, MA).

III In Vitro Test Results

The healthy-rest case is simulated by setting the heart rate, driving pressure and vacuum pressure of the left ventricular simulator at 60 beats per min (bpm), 120mmHg and –4mmHg respectively. Then other equipments were adjusted until the similar response to that of a healthy person in rest condition can be obtained. The CHF-rest case was simulated by changing the driving pressure and vacuum pressure of left ventricular simulator to 60mmHg and –3mmHg respectively while maintaining other settings and equipments as in the healthy-rest case. Then CHF-exercise case was simulated based on the CHF-rest case by changing the heart rate and vacuum pressure of left ventricular simulator to 95bpm and –4mmHg respectively. The TPR was decreased by 40% in exercise. The period of systole was set to be 40% of the heartbeat for all simulated scenarios [3]. The test rests were plotted in Fig 2.

In the simulated CHF-rest case, the total peripheral flow (TPF) was elevated by the pump from 3.38L/min to 5.4L/min. The left ventricular end-diastolic pressure (LVPED) was decreased from 17mmHg to 6.5mmHg, which is within the safe range –3~15mmHg specified by the two dashed line in Fig 2. The aortic pressure (AOP) was restored from 54mmHg to 105.1mmHg. The values of these three parameters were close to those of the simulated healthy-rest case, as 5.2L/min, 5.4mmHg, and 99.6mmHg respectively. In the simulated CHF-exercise case, the LVPED was maintained by the pump at 7.2mmHg, within the specified safe range. AOP was 104.5mmHg, close to the value of the simulated healthy-rest condition. The TPF was elevated by the pump to 8.34L/min as the value of TPR in the exercise was smaller than that in the rest condition. The pump speed in different activity levels was stable, while undergoing the transition period, which was not shown in Fig 2, was somewhat long (around 60 sec). Pump flow was always positive, which implied no blood recirculation.

IV Conclusions

In vitro test results showed that the designed adaptive controller for the long-term LVAD provided the desired blood flow, restored the left ventricle end-diastolic pressure to within safe range, and maintained the aortic pressure for CHF patients in the simulated rest and exercise conditions. The controller needs to be explored in more depth to ensure a stable working speed for each activity level and a faster response to shift from one activity level to another. The steady state estimation error of the aortic pressure was not zero as expected, due to the modeling error in the estimator of [1], which is expected to improve after the incorporation of adaptive estimation of parameter.

Acknowledgement

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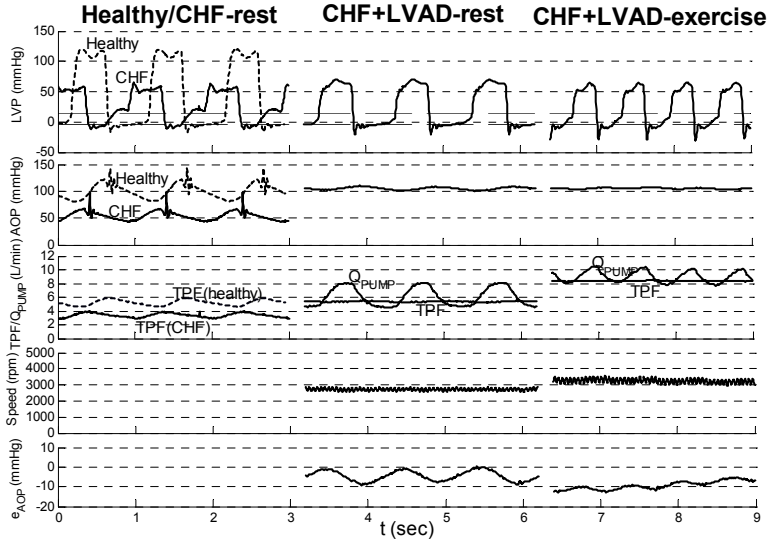

Figure 2. In Vitro Test Results on MY2 Pump. (LVP: left ventricular pressure, AOP: aortic pressure, TPF: total peripheral flow, Q_{PUMP}: pump flow rate, Speed: pump rational speed, e_{AOP}: estimation error of aortic pressure) Dashed lines: Healthy-rest case. Solid lines: CHF cases.