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A Method to Increase the Pulsatility in Hemodynamic Variables in an LVAD Supported Human Circulation System

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Abstract— **Left Ventricular Assist Devices (LVADs) generally operate at a constant speed in the human body. This causes a decrease in the pulsatility of hemodynamic variables. To increase the pulsatility a stepwise change was applied to the LVAD operating speed over a cardiac cycle. To do this, a numerical cardiovascular system model and a pump model were used. The model was developed by considering the static characteristics of the MicroMed DeBakey LVAD. First, the simulations were performed at constant operating speeds, 8500 rpm, 9500 rpm and 10500 rpm. Pulsatility indexes were calculated for left ventricular (LV) pressure, aortic pressure, LV volume and LVAD flow. Cardiac output (CO) was calculated at constant operating speed and these values used for comparing the pulsatility indexes with stepwise and constant operating speeds. The LVAD was operated at two different constant speeds in the stepwise operating speed simulations. Low and high operating speeds were adjusted so as to obtain the same cardiac output values with the constant operating speed simulations. The operating speeds in the simulations were 7800-11250 rpm, 9300-11250 rpm and 10300-11250 rpm. The same cardiac output values were obtained with an increase in the pulsatility of the hemodynamic variables without significant changes in their shapes except the LVAD flow. The obtained results show that it is possible to obtain more physiological results by applying a stepwise change to LVAD operating speed over a cardiac cycle.**

Keywords— **Heart pumps, LVADs, pulsatility, static characteristics, stepwise speed control.**

I. INTRODUCTION

Left Ventricular Assist Devices operate at a constant speed in the human body. This speed causes a decrease in pulsatility in the hemodynamic variables such as LV pressure, LV volume, aortic pressure, flow rate of the LVAD. In full support the aortic valve remains closed over a cardiac cycle and all the blood flows through the LVAD [1]. The remaining pulsatility in an LVAD assisted heart exists because of contractions of the LV. This low pulsatility condition, may lead to aortic insufficiency and other long-term vascular complications. More physiological LVAD operation may alleviate these problems.

Several attempts to improve the assistance of the LVADs in the human cardiovascular system have been described in literature. Moscato et al. developed a control strategy that provides an explicitly definable loading condition for the failing ventricle [2]. The studies show that there is a relation between the motor current and hemodynamic variables in an LVAD assisted heart. This relation was used to develop LVAD control strategies [2-6]. The LVADs show deleterious effects such as suction when the operating speed reaches a relatively high value. There are studies to detect and prevent the suction in the literature [7-11]. These studies show sufficient support to the circulation system and prevent suction.

Pulsatility in the hemodynamic variables decreases in an LVAD supported heart however pulsatility is a desired effect in a VAD assisted heart and can be obtained by using a pulsatile flow VAD. In a continuous flow VAD pulsatility diminishes and afterload increases [12]. In this paper, a different approach is presented to improve the long-term support capability of the LVAD. A stepwise operating speed change was applied to obtain pulsatility in hemodynamic variables over a cardiac cycle.

II. METHOD

To apply a stepwise operating speed over a cardiac cycle, a numerical human cardiovascular system (CVS) model and a numerical model for Micromed DeBakey LVAD were used. The operating speed was increased instantly when LV pressure reaches its peak value and kept constant until it reaches the lowest value. When LV pressure reaches its lowest value, the LVAD operating speed was adjusted to the low value again and kept at this value until peak LV pressure was observed again. The results were compared with constant speed operation, rendering the same overall cardiac output. For an accurate comparison pulsatility indexes (PI) were defined for the hemodynamic variables.

The numerical CVS simulation model consists of an active left ventricle (LV) and right ventricle (RV), left atrium, right atrium, aortic valve (AV), mitral valve (MV), tricuspid valve (TV), pulmonary valve (PV), aorta, systemic veins, pulmonary arteries and pulmonary veins. The equivalent electric analogue is given in Fig.1. Abbreviations are given in Table1.

S. Vlad and R.V. Ciupa (Eds.): MEDITECH 2011, IFMBE Proceedings 36, pp. 328–331, 2011.
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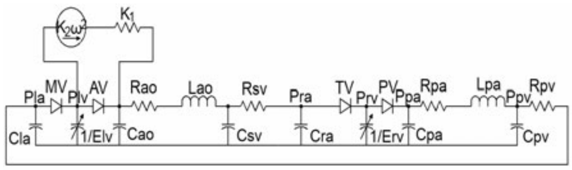

Fig. 1 Equivalent electric analogue of CVS model and LVAD

Table 1 Symbols

Nomenclature		Subscripts	
AV	Aortic valve	ao	aorta
C	Compliance	la	left atrium
e	Activation function	lv	left ventricle
E	Elastance	pa	pulmonary arteries
K	Pump coefficeint	pv	pulmonary veins
L	Inertance	ra	right atrium
MV	Mitral valve	rv	right ventricle
PV	Pulmonary valve	sv	systemic veins
Q	Flow rate	d	diastolic
R	Resistance	s	systolic
T	Heart beat period,	1	peak systole
t	instantaneous time	1	number of pump coefficient
TV	Tricuspid valve	2	peak diastole
ω	Rotation speed	2	number of pump coefficient
ΔP	Pressure difference		

Parameter values and the equations for compartments are taken from the available literature and all the parameter values and equations were used in the numerical model can be found in [13-16]. Elastance and activation functions of the ventricles were taken from [17]. The elastance function (1) of the ventricles is calculated by using the activation function (2). The activation function describes the contraction and relaxation phases in the ventricles.

$$E = E_d + \{(E_s - E_d)/2\}e \tag{1}$$

$$e = \begin{cases} 1 - \cos(t\pi / T_1), 0 \le t < T_1 \\ 1 + \cos\{(t - T_1)\pi / (T_2 - T_1)\}, T_1 \le t < T_2 \\ 0, T_2 \le t < T \end{cases} \tag{2}$$

The symbols are referenced in Table 1. The same equation was used in both ventricle models but the parameter values were different. Es and Ed for the LV were 2.5 mmHg/mL and 0.1 mmHg/mL respectively. Es and Ed for the RV were 1.15 mmHg/mL and 0.1 mmHg/mL respectively [17]. T was adjusted to 0.8 sec and kept constant in all the simulations. T_1 was adjusted 0.3*T and T_2 was adjusted 0.45*T. Dilated cardio-myopathy was induced by reducing the Es value for both ventricles to 0.5 mmHg/mL.

A numerical pump model was developed to simulate the MicroMed DeBakey LVAD by considering the static characteristics of the pump. Static characteristics of this pump are given in Fig. 2. Detailed information about the measurements of pressure across the LVAD can be found in [18]. The model used in the simulations is given below:

$$\Delta P = K_1 Q + K_2 \omega^2 \tag{3}$$

The values of K_1 and K_2 were estimated to be -0.264 mmHg/mL/s and 0.0035 mmHg/s^2 respectively.

The numerical pump model was implemented in the CVS model and simulations were performed for constant operating speed at 8500, 9500 and 10500 rpm. After completing the simulations at constant operating speeds, simulations were performed for stepwise LVAD operating speeds. In the stepwise operating speed simulations the LVAD switched to high speed at the peak LV pressure and kept constant until LV pressure reaches its minimum value. Three different simulations were performed at 7800-11250 rpm, 9300-11250 rpm and 10300-11250 rpm operating speeds to obtain the same cardiac outputs as observed in the simulations for constant operating speeds. The maximum speed was set to 11250 rpm to prevent the suction. The LVAD operating speed and LV pressure are given in Fig 2.

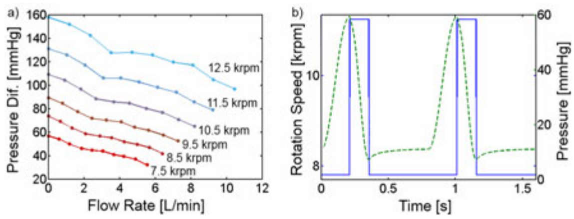

Fig. 2 a) Static characteristics of the MicroMed DeBakey LVAD, b) LVAD speed (-continuous line), LV pressure (--dashed line)

To determine and make a comparison between the pulsatility in the hemodynamic variables, pulsatility indexes were calculated as below.

$$PI = \{X_{max} - X_{min}\} / \{(X_{max} + X_{min})/2\} \tag{4}$$

The parameter X is used for the hemodynamic variables that were considered in the simulations; LV pressure, aortic pressure, LV volume and LVAD flow. The subscripts of max and min in the (4) denote maximum and minimum values of these hemodynamic variables. Simulations were performed using the Matlab Simulink tool. Solver and maximum step size were set to ode15s and 0.0002 s respectively.

III. Results

Simulations were performed for healthy and pathological conditions without LVAD support first. LV pressure, aortic pressure, LV volume and cardiac output (CO) for healthy and pathological conditions are given in Fig.3 and summarized in Table 2.

LV pressure, aortic pressure and LV volume under assisted conditions at constant speeds are given in Fig 4.

For increasing constant LVAD operating speed LV pressure decreases and aortic pressure increases with increasing LVAD operating speed (Fig. 4). End-systolic and end-diastolic volume of the LV decrease with increasing constant operating speed. LV pressure, aortic pressure and LV volume under assisted conditions at stepwise changing speed are given in Fig 5.

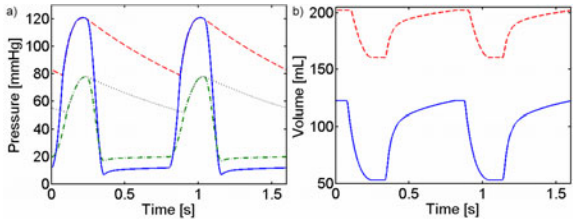

Fig. 3 a) LV pressure (- healthy, -. pathological), aortic pressure (-- healthy, : pathological) b) LV volume (- healthy, -- pathological)

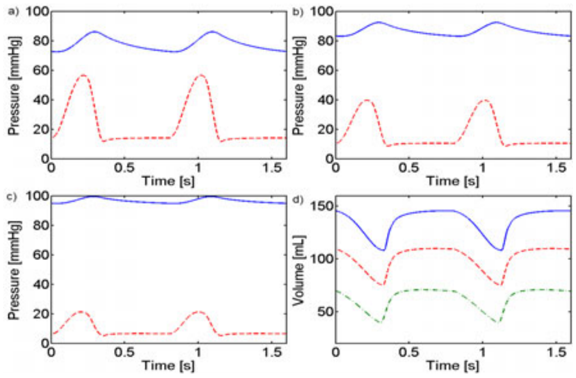

Fig. 4 a) LV pressure and aortic pressure at 8500 rpm, b) LV pressure and aortic pressure at 9500 rpm, c) LV pressure and aortic pressure at 10500 rpm, (-- LV pressure, -aortic pressure), d) LV volume at constant speed (- 8500 rpm, -- 9500 rpm, -. 10500 rpm)

Table 2 Simulation results

	Plv[mmHg]	Pao[mmHg]	Vlv[ml]	CO[mL/s]
Healthy	7-120	79-121	53-122	86.3
Pathological	17-78	58-78	160-202	52.5

The shapes of the hemodynamic signals at the stepwise operating mode are similar to the constant operating speeds over a cardiac cycle. Stepwise change of the LVAD operating speed hardly changes the shape of the hemodynamic signals. However the amplitude of the aortic pressure signal doubles. The LVAD flow for constant and stepwise operating speeds are given in Fig. 6.

The shape of the LVAD flow changes significantly due to sudden change in the LVAD operating speed. The PI values of the LV pressure, aortic pressure, LV volume and LVAD flow were calculated according to equation (4). The change of PI values for the considered hemodynamic variables at the constant operating speeds and stepwise operating speed are given in Fig. 7.

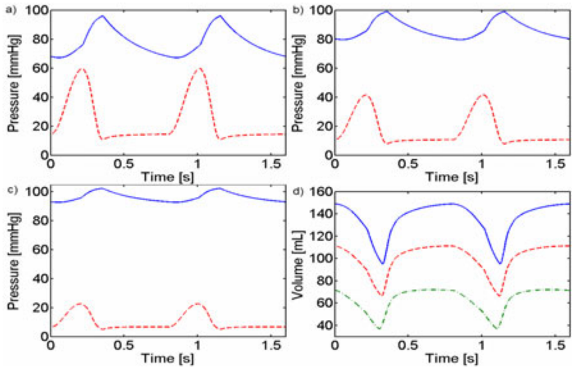

Fig. 5 a) LV pressure and aortic pressure at 7800-11250 rpm, b) LV pressure and aortic pressure at 9300-11250 rpm, c) LV pressure and aortic pressure at 10300-11250 rpm, (--LV pressure, -aortic pressure), d) LV volume (- 7800-11250 rpm, --9300-11250 rpm, -.10300-11250 rpm)

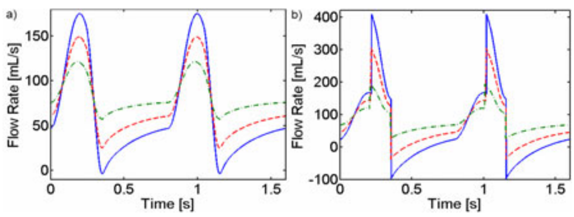

Fig. 6 a) LVAD flow at constant operating speed (- 8500 rpm, -- 9500 rpm, -. 10500 rpm), b) LVAD flow at stepwise operating speed (- 7800-11250 rpm, -- 9300-11250 rpm, -. 10300-11250 rpm)

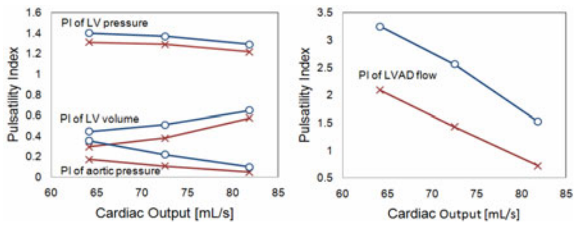

Fig. 7 PI of the LV pressure, aortic pressure, LV volume and LVAD flow for constant operating speed and stepwise operating speed (o: stepwise speed change, x: constant speed)

As shown in Fig 6, maximum value of the LVAD flow increases and minimum value decreases to obtain same mean CO values with the constant operating speed mode at stepwise operating speed. The peak values are not excessively high, the human CVS can handle these short term peak flows because of the large compliance of arterial system.

Stepwise change in the operating speed over a cardiac cycle provides increase in the pulsatility in all the hemodynamic variables considered (Fig. 7). The systolic aortic pressure is increased if the operating speed changes stepwise over a cardiac cycle. PI values decrease for increasing cardiac outputs in both constant and stepwise change of speeds except for the LV volume. The difference between the maximum and minimum values in hemodynamic variables decreases for constant and stepwise operating speeds for increasing cardiac output values.

IV. Discussion

In this paper a method was proposed and applied to increase the pulsatility of the hemodynamic variables in an LVAD assisted circulation system. It is possible to increase pulsatility and systolic aortic pressure if the operating speed changes stepwise without a significant effect on the shape of the hemodynamic variables except the LVAD flow. CO values did not change indicating that support quality of the LVAD is improved. In this study high speed was kept constant at 11250 rpm and the lower speed was changed. The operating speeds could be adjusted by considering heart rate, the inlet and the outlet pressure of the LVAD or any other parameter can be measured or estimated to obtain more physiological results and a better support. Also a pump model was developed by using the static characteristics of MicroMed DeBakey LVAD. A dynamic pump model would give better and more accurate simulation results, because dynamic pump load changes due to contractions of LV. In the simulations operating speed was changed instantaneously which is impossible in a real application. In real pumps, there will be a transition time from one speed level to next. To develop controllers capable of achieving this are subject of ongoing research.

At constant LVAD operating speeds aortic valve incompetence would occur due to change of pulsatility [19]. At stepwise operating speed mode pulsatility increases and it can potentially be a method to solve insufficiency problems in an LVAD supported human CVS.

Acknowledgement

This study is part of the MeDDiCA project and funded under FP7, People Programme, Marie Curie Actions. Grant agreement PITN-GA-2009-238113.

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