Simulation of Axial Flow Left Ventricular Assist Device’s Control Algorithm Used to Assist Different Levels of Heart Failure Based on the Circuit Model

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Abstract. Modelling blood circulation is difficult. Due to the similarity of blood circulation and circuit loop, a numerical model coupled with the cardiovascular system and the left ventricular assist device is used to study the control algorithm of left ventricular assist devices in this study. According to severity, heart failure can be divided into three levels, and is simulated by varying the time-varying capacitance. Most of the left ventricular assist devices adopt the control algorithm of constant speed, which can reduce the pulsation of aortic pressure, and it is especially obvious in level III heart failure. We compare the positive pulse mode and the constant speed mode, and the results show that the positive pulse could increase systolic blood pressure and reduce diastolic blood pressure, which is more in line with the human aortic pulsation, and is more suitable for patients with high level of heart failure.

1. Introduction
Heart failure (HF) is a very dangerous clinical syndrome caused by failure of cardiac pumping blood, which is the result of the advanced development of cardiovascular disease. The incidence of HF increases with age. At present, the main methods for the treatment of heart failure include drug therapy, Cardiac Resynchronization Therapy (CRT), Mechanical Circulatory Support (MCS) and Heart Transplantation (HT) [1].

In China, the research on axial bleeding pump is relatively late, but with the joint efforts of domestic universities and scientific research institutions, the research and development of axial bleeding pump in China has also made great progress. Changyan Lin et al. from the Affiliated Hospital of Capital Medical University designed an axial bleeding pump named "Type II axial flow VAD" using computer-aided design method. Zhong Yun et al. from Central South University designed an aortic valve axial bleeding pump. Kaiyun Gu and Yu Chang et al. from Beijing University of Technology designed an aortic valve axial bleeding pump using the lumped parameter model to analyse the hemodynamics under different control strategies.

Based on the degree of damage to the heart, there are three levels of heart failure [1]. The symptoms of heart failure at different levels are list, as shown in Table 1. When the ventricular assist device is used to assist the failing heart, the general evaluation condition is to make the average aortic pressure and cardiac output of the heart failure patients reach the level required by normal physiology [2]. Therefore,
the use of constant speed to control the operation of the blood pump may result in low aortic pressure pulsation, which may lead to some long-term clinical complications [3].

| Level | Symptom |
|-------|---------|
| I     | Physical activity is slightly limited with symptoms of fatigue, shortness of breath, and angina pectoris. Rest is asymptomatic. |
| II    | Physical activity is significantly limited and rest is asymptomatic, but any excess will cause symptoms. |
| III   | Inability to engage in physical activity, symptoms will occur at rest, especially during physical activity. |

Due to ethical limitations in animal or human trials, numerical model using the cardiovascular system coupled with the left ventricular assist device was used. Axial flow left ventricular assist device was selected to analyse different levels of heart failure. Its positive pulse control algorithm was studied and compared with constant speed [4]. This numerical model method is also applicable to other types of LVADs.

2. Materials and Methods

As shown in Figure 1, the blood circulatory system is equivalent to a circuit model because of the similarity between them. In this model, voltage and current are used to represent the blood pressure and blood flow, inductance is used to represent the blood flow inertia, resistance is used to represent the friction loss suffered by the blood flow, and capacitance is used to represent the compliance of the heart chamber and blood vessels. Considering the characteristics of the mitral valve and the aortic valve controlling the one-way flow of blood, a resistor and an ideal diode are used in series to represent the opening and closing state of the heart valve [5, 6]. Axial flow LVAD model connects left ventricle and aorta, and the pressure difference between the inlet and outlet of the pump is expressed by H:

$$H = \beta_0 x_6 + \beta_1 \frac{dx_6}{dt} + \beta_2 \omega^2$$  \hspace{1cm} (1)

$x_6$ is the flow rate of the pump (ml/s); $\omega$ is the operating speed of the pump (revolutions per minute, rpm).
Table 2. State Variables

| State Variables | Name       | physiological meanings               |
|-----------------|------------|-------------------------------------|
| x₁(t)           | LVP(t)     | Left Ventricular Pressure (mmHg)    |
| x₂(t)           | LAP(t)     | Left Atrial Pressure (mmHg)         |
| x₃(t)           | AP(t)      | Arterial Pressure (mmHg)            |
| x₄(t)           | AOP(t)     | Aortic Pressure (mmHg)              |
| x₅(t)           | Q ₁(t)     | Cardiac output (ml/s)               |
| x₆(t)           | Q ₂(t)     | Pump flow (ml/s)                    |

\[
\begin{align*}
\frac{dx_1(t)}{dt} &= \left[ r\left(x_2(t) - x_1(t)\right) - x_6(t) - x_1(t) \right] \frac{dC(t)}{dt} \\
\frac{dx_2(t)}{dt} &= \left[ x_3(t) - x_2(t) - r\left(x_2(t) - x_1(t)\right) \right] / C_R \\
\frac{dx_3(t)}{dt} &= \left[ x_5(t) - x_3(t) - x_2(t) \right] / C_R \\
\frac{dx_4(t)}{dt} &= \left[ x_6(t) - x_5(t) \right] / C_A \\
\frac{dx_5(t)}{dt} &= \left[ x_4(t) - x_3(t) - R_c * x_5(t) \right] / L_S \\
\frac{dx_6(t)}{dt} &= \left[ x_4(t) - x_1(t) - \beta_0 * x_6(t) - \beta_2 * \omega^2 \right] 
\end{align*}
\]

(2)

\[r(x) \text{ represents the ramp function:} \]
\[
r(x) = \begin{cases} 
  x, & x \geq 0 \\
  0, & x < 0 
\end{cases}
\]

The physiological meanings of the state variables are listed in Table 2, and the physical meanings of the parameters are listed in Table 3.

Table 3. Nomenclature

| Parameters | physiological meanings               |
|------------|-------------------------------------|
| R₅         | Systemic Vascular Resistance        |
| R₆         | Mitral Valve Resistance             |
| R₇         | Aortic Valve Resistance             |
| R₈         | Characteristic Resistance           |
| C(t)       | Left Ventricular Compliance         |
| Cₛ         | Left Atrial Compliance              |
| Cₘ         | Systemic Compliance                 |
| Cₙ         | Aortic Compliance                   |
| Lₙ         | Inertance of blood in Aorta         |
| Dₘ         | Mitral Valve                        |
| Dₙ         | Aortic Valve                        |
| Rₙ         | Inlet Resistance of Cannulae        |
| Rₒ         | Outlet Resistance of Cannulae       |
| Lᵢ         | Inlet Inertance of Cannulae         |
| Lₒ         | Outlet Inertance of Cannulae        |
| Rₚ         | Suction Resistance                  |

\[C(t) = 1 / [(E_{max} - E_{min})E_n + E_{min}] \]

(4)
The $E_{\text{max}}$ and $E_{\text{min}}$ in the time-varying capacitance ($C(t)$) are the ratios of the left ventricular end-systolic pressure and end-diastolic pressure and their corresponding volumes respectively, and the failing heart is simulated by changing the $E_{\text{max}}$. In this paper, the cardiac cycle is 0.8s (75bpm), systolic is 0.3s, and diastolic is 0.5s. $E_{\text{max}}$ was 2.0 mmHg/ml for normal heart, 1.5 mmHg/ml for level I heart failure, 1.0 mmHg/ml for level II heart failure, and 0.5 mmHg/ml for level III heart failure. It is known that under normal physiological conditions, the physiological parameters of a healthy heart in one cardiac cycle are as follows: the diastolic blood pressure of the aorta is 60-90 mmHg, the systolic blood pressure is 90-140 mmHg, and the cardiac output is 4.5-6L/min [5]. In constant speed mode, LVAD velocity remains constant throughout the cardiac cycle. For the positive pulse mode, the peak velocities of LVAD are achieved during the systolic phase of the heart. In order to compare the positive pulse mode and constant speed mode of LVAD, different modes are used to make different levels heart failure reach the level of normal heart. For constant speed mode, 10000 rpm is used for Level I HF, 11000 rpm for Level II HF, and 11500 rpm for Level III HF. For the positive pulse mode, the trapezoidal wave as shown in Figure 2 is adopted, which rises at 0.05s, reaches the maximum at 0.15s, begins to decline at 0.3s, and reaches the minimum at 0.4s. The minimum value of the three heart failure levels is all 10000 rpm, and the maximum value of the I level heart failure is 12000 rpm, the maximum value of the II level heart failure is 13500 rpm, and the maximum value of the III level of is 15000 rpm.

3. Results & Discussion

![Figure. 2. positive pulse mode of LVAD](image-url)
Figure. 3. The waveforms of LVP, AOP and cardiac outputs under normal heart and three levels of heart failure

LVP, AOP, and cardiac output simulation for normal heart and 3 levels of heart failure are depicted in Figure 3. The average cardiac output of normal heart in one cycle is 4.51 L/min, with aorta systolic pressure of 108.36 mmHg and diastolic pressure of 71.76 mmHg, within the normal range described above. The average cardiac output in one cycle of I level heart failure is 4.17 L/min, the aorta systolic blood pressure is 101.04 mmHg, and the diastolic blood pressure is 67.06 mmHg, the cardiac output is not in the normal range. The average cardiac output in one cycle of II level heart failure is 3.52 L/min, the aorta systolic blood pressure is 87.86 mmHg, and the diastolic blood pressure is 58.28 mmHg, which are not in the normal range. The average cardiac output in one cycle of III level heart failure is 2.33 L/min, the aorta systolic blood pressure is 62.80 mmHg, and the diastolic blood pressure is 42.50 mmHg, which is far below the normal range. The obtained data can also support the symptoms of different levels of heart failure described in Table 1.

Figure. 4. The waveforms of LVP, AOP and pump flow under constant speed and positive pulse of I level heart failure

The LVP, AOP, and pump flow of level I heart failure at constant speed and positive pulse are described in Fig. 4. At constant rotation speed, the average cardiac output flow in one cycle is 4.86 L/min, the systolic pressure of aorta is 103.93 mmHg, and the diastolic pressure is 85.42 mmHg. Under
the positive pulse, the average cardiac output flow is 4.95 L/min, the aortic systolic pressure is 106.38 mmHg, and the diastolic pressure is 86.74 mmHg. Cardiac output, systolic blood pressure and diastolic blood pressure are all up to standard in both modes. Because level I heart failure is not severe, both modes can achieve a good auxiliary effect, in line with the human body pulsation.

Figure 5. The waveforms of LVP, AOP and pump flow under constant speed and positive pulse of II level heart failure

The LVP, AOP, and pump flow of level II heart failure at constant speed and positive pulse are described in Fig. 5. At constant rotation speed, the average cardiac output flow in one cycle is 4.71 L/min, the systolic pressure of the aorta is 95.38 mmHg, and the diastolic pressure is 87.06 mmHg. Under the positive pulse, the average cardiac output flow in one cycle is 4.82 L/min, the aortic systolic pressure is 102.32 mmHg, and the diastolic pressure is 83.84 mmHg. Cardiac output, systolic blood pressure and diastolic blood pressure are all up to standard in both modes. level II heart failure can be clearly seen, positive pulse mode pulsation is better, more consistent with the body.

Figure 6. The waveforms of LVP, AOP and pump flow under constant speed and positive pulse of III level heart failure

The LVP, AOP, and pump flow for level III heart failure at constant speed and positive pulse are described in Fig. 6. At constant rotation speed, the average cardiac output flow in one cycle is 4.82 L/min, the systolic pressure of the aorta is 93.02 mmHg, and the diastolic pressure is 85.98 mmHg. Under the
positive pulse, the average cardiac output flow is 4.92 L/min, the aortic systolic pressure is 104.04 mmHg, and the diastolic pressure is 83.83mmHg in one cycle. Cardiac output, systolic blood pressure and diastolic blood pressure are all up to standard in both modes. The constant speed of level III heart failure is nearly straight, and the pulsation in positive pulse mode is consistent with human body.

Compared with three levels of heart failure, it can be found that with the increase of the severity of heart failure, the heart will be more dependent on the assistance of LVAD as its pumping ability gradually decreases. In the case of higher grades of heart failure, LVAD requires higher rotational speed, but if it works at a high speed for a long time, the pressure and blood flow in the aorta will almost lose the ability to pulsate, leading to later complications, such as aortic insufficiency, gastrointestinal bleeding, hemorrhagic stroke and so on [7].

4. Conclusions

In this paper, a numerical model based on the coupling of the cardiovascular system and the left ventricular assist device is proposed to investigate the performance and hemodynamic characteristics of the two control modes under three levels of heart failure. According to clinical practice, we choose two LVAD working modes, namely constant speed mode and positive pulse mode. The results showed that mean cardiac output and aortic pressure were within the normal range. With the increase of the level of heart failure, compared with the constant speed, the positive pulse mode is more consistent with the body's pulsation, and can play a very good role in helping people to restore normal life in serious heart failure.

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