# Simulation study and function analysis of the dynamic aortic valve*

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**Abstract** The dynamic aortic valve (DAV) is a new left ventricular assist device, a micro-axial blood pump implemented at the position of the aortic valve, pumping blood from the left ventricle into the aortic artery. The present dynamic aortic valve operates at 7 different rotation speeds, ranging from 3000 r/min (speed 1) to 9000 r/min (speed 7). Because *in vivo* experiments need a lot of live animals and take a long period of time, modeling and simulation have been widely used to simulate and analyze hydra-dynamic property of the DAV and its assisting effects. With the measurements from the mock circulatory loop, a mathematic model of the DAV is established and embedded into the previously developed canine circulatory system. Using this model, the effect of the DAV on the failing heart at each rotation speed level is investigated. The vital cardiac variables are computed and compared with *in vivo* experimental results, which are in good agreement with an acceptable difference mostly 15%. The establishment of the DAV model and its simulation are useful for further improvement of the DAV device.

**Keywords: dynamic aortic valve, mathematic model, computer simulation.**

Since Debakey[1] firstly inserted a mechanical cardiac assist pump into human chest, many types of micro-pumps, including Hemopump[2], Micromed DeBakey VAD[3,4], Jarvik2000[5,6] and Incor Ventricular Assist Device[7], have been designed and applied to patients in clinical practice.

Usually, the power to drive the pumps is transmitted through a percutaneous power cable. In 1996, a new cardiac assist device, named dynamic aortic valve, was introduced by Li et al.[8], and its first *in vivo* trial in dogs was conducted[9].

The dynamic aortic valve (DAV) consists of an external drive unit and an internal pump, which are separated from each other without any power cable connection. The pump is made of a support cage, a unit of magnetic rotor and impellers. The unit will rotate in the presence of revolving magnetic field generated by an external drive unit. The DAV is 22 mm in diameter and 30 mm in length, and is inserted into the position of the aortic valve, pumping blood from the left ventricle into the aorta. Owning to its small volume, compact structure and enough flux, DAV is a promising assist device. However, the operation of the DAV is still under investigation and improvement.

In this paper, we introduce a dynamic model for the DAV based on experimental data derived from the mock circulatory loop. This model is inserted into a canine cardiovascular model constructed by our group[10,11], and its effects on various cardiac variables at different levels of assistance are assessed. The results obtained are compared with the *in vivo* experimental data.

## 1 Model description

### 1.1 Mock circulation loop

In 2002 we built a mock circulatory loop for the DAV and primed it with 30% glycerol solution at 20℃. In this mock circulation, the DAV was driven by a parallel whirling magnet at a distance of 40 mm, and the pressure head could be regulated from 0 mmHg to 80 mmHg. The flow-pressure head relationship was tested when the DAV operated at seven speeds, ranging from 3000 r/min (speed 1) to 9000 r/min (speed 7), with an increment of 1000 r/min. A nearly linear relationship between the flow and pressure head was found with its operating at a constant speed.

According to a steady model of Hemopump, proposed by Li[12], a relationship between the pump flow $Q_{steady}$ and the pressure head $\Delta P_{stat}$ is demonstrated as the following equations:

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$$Q_{\text{steady}} = Q_n - \frac{1}{R_n}\Delta P_{\text{stat}} = A_n - B_n \cdot \Delta P_{\text{stat}}, \quad (1)$$

$$Q_n = A_n \quad \text{and} \quad R_n = 1/B_n, \quad (2)$$

where $Q_n$ ($A_n$) is a constant flow source and $R_n(1/B_n)$ a resistance, both of which are considered only related to rotation speed of the pump. $Q_n$ and $R_n$ of each speed level were calculated based on linear fit to the mock circulatory experimental data, which are shown in Table 1.

Table 1. Values of coefficients in (1) and (2) at seven speed levels

| | Speed level | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| $Q_n$(mL·s$^{-1}$) | 49.88 | 68.18 | 86.47 | 104.78 | 123.06 | 141.36 | 159.66 |
| $R_n$(mmHg·s·mL$^{-1}$) | 0.4239 | 0.6005 | 0.7771 | 0.9538 | 1.1304 | 1.3070 | 1.4836 |

1.2 DAV model

When the DAV is inserted into a living circulatory system, we should consider the inertial property of the blood, which is defined as an inertia $H$[12] in the dynamic model of the DAV, as shown in Fig. 1.

$$H = L\frac{\rho}{A} = L\frac{\rho}{\pi bd/4} = 0.7673 \times 10^{-3}\ \text{mmHg} \cdot \text{s}^2/\text{mL}, \quad (3)$$

where $L$ is the length of the DAV, $A$ the cross-sectional area, $\rho$ the fluid density, $d$ the outer diameter and $b$ the inner diameter of the DAV. Therefore, the dynamic model of DAV includes three components: constant flow source, resistance and inertia.

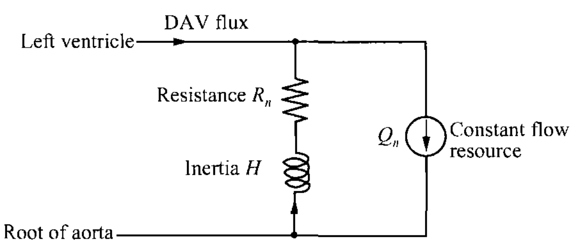


Fig. 1. Dynamic model of the DAV.

1.3 Insertion of the DAV model into the canine cardiovascular system

The canine cardiovascular system[10,11] consists of four heart chambers, a pulmonary circulation unit, an aortic valve and aortic root, 11 aortic segments, venous and peripheral vascular systems. When the DAV is implanted into the aortic valve position, the aortic valve should be remaining open or even removed. Thus, in the model, the DAV dynamic model will replace the aortic valve (Fig.2). The inlet of the DAV is inserted into the left ventricle, and the outlet is located at the descending aorta.

The model of the left ventricle with regional ischemia was proposed by Zhou et al.[10] previously. In this model, the left ventricle is functionally divided into two non-physiological compartments, one consisting of all the normal myocardium, and the other consisting of all the ischaemic myocardium. In this paper, we use $R_m$ to denote the ratio of the ischemic myocardial mass to the total myocardial mass, and we set $R_m$ to be 30% to simulate the left ventricle with slight ischemia.

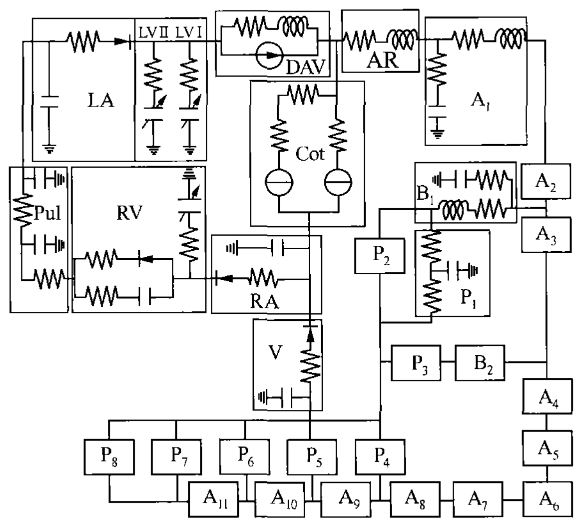


Fig. 2. Insertion of the DAV model into the canine circulatory system. LA, left atriam; LVH, normal compartment of left ventricle; LVI, ischaemic compartment of left ventricle; DAV, dynamic aortic valve; AR, aortic root; An, aortic segments; Bn, aortic branch segments; Pn, peripheral vascular segments; V, venous system; RA, right atrium; RV, right ventricle; Pul, pulmonary circulation; Cor, coronary artery.

## 2 Computer simulation

The subject of the computer simulation was a dog in horizontal position, with minor regional ischemia ($R_m$ = 30%). The peak elasticity of the normal compartment was set to be 5 mmHg·mL$^{-1}$, and the peak elasticity of the ischemic compartment was set to be 1 mmHg·mL$^{-1}$. The heart rate was set to be 120 beats per min. The computer program was written in Delphi language and run on a Windows compatible computer of CPU 2.40 GHz.

The simulation interval for computation was 0.001 s. During each interval, flow and volume of each block were computed and updated sequentially according to cardiovascular circulation sequence. The simulation program ran for 40 beats until the whole system achieved dynamic stabilization.

## 3 Results

### 3.1 Pump flow and pressure difference during an ischemic circulation cycle

The DAV always operated at a constant rotation speed ranging from 3000 r/min (speed 1) to 9000 r/min (speed 7) with an increment of 1000 r/min.

The flow-pressure difference ($Q-\Delta P$) relationship of the DAV during one cardiac cycle with minor regional ischemia ($R_m = 30\%$) at speed 3, 5 or 7 is shown in Fig. 3, which indicates that, at each speed level, hysteresis of the DAV is much smaller than HP31 or other left ventricular assist devices[13], since the inertial property of the DAV is about only 5.8% of the HP31. When speeding up, the hysteresis of the loop decreases. When the DAV was operated at 9000 r/min (speed 7), the flow-pressure difference curve for systolic period is coincident with the curve for diastolic period.

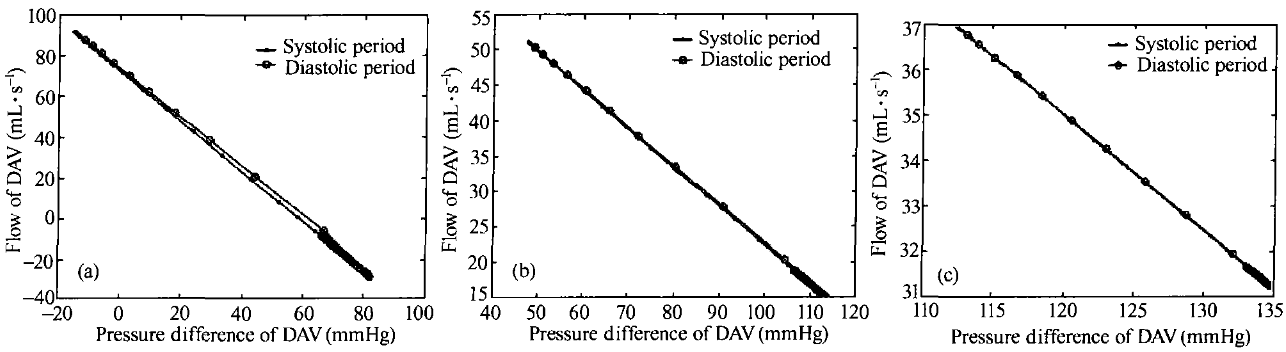


Fig. 3. Relationship of pump flow-pressure difference during a cardiac cycle with minor regional ischemia ($R_m = 30\%$) at speed 3 (a), speed 5 (b) and speed 7 (c).

Fig. 4 shows the DAV flux during one cardiac cycle at speeds 3—7. The pulsation can be observed at each speed level, especially at low speed levels. With speeding up of the DAV rotation, the pulsation of the DAV flow decreases, while the average flux increases. Besides, huge backflow happened at the end of systole when the DAV worked at speed 3 and speed 4. Therefore, based on these results, the DAV should operate at a speed above 6000 r/min in order to prevent the backflow to the failing left ventricle.

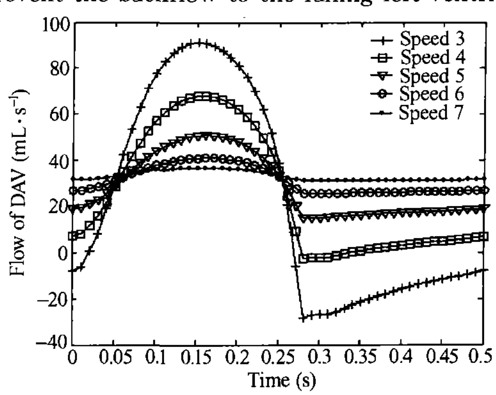


Fig. 4. DAV flux during a cardiac cycle when it operates at one of five speed levels.

### 3.2 Effects of the DAV on various cardiac parameters

The cardiac parameters changed differently when the DAV rotated at different speeds. Fig. 5(a) shows the aortic pressure during a cardiac cycle at each of the five rotation speeds. From speed 3 on, the mean aortic pressure is higher than that of the ischemic heart without assistance. As the rotation speed becomes higher, the mean aortic pressure becomes higher too, while the pulsation decreases. The same changes have been observed in clinical experiments with other left ventricular assist devices, such as Hemopump[14,15].

Fig. 5(d) depicts the pressure-volume relationship of left ventricle during one cardiac cycle at 5 rotation speeds. The higher rotation speeds (speed 3 and up) result in a smaller volume of the left ventricle. However, the left ventricular volume never approaches zero, so this will not cause "over-unload" observed in the experiment with Hemopump[15].

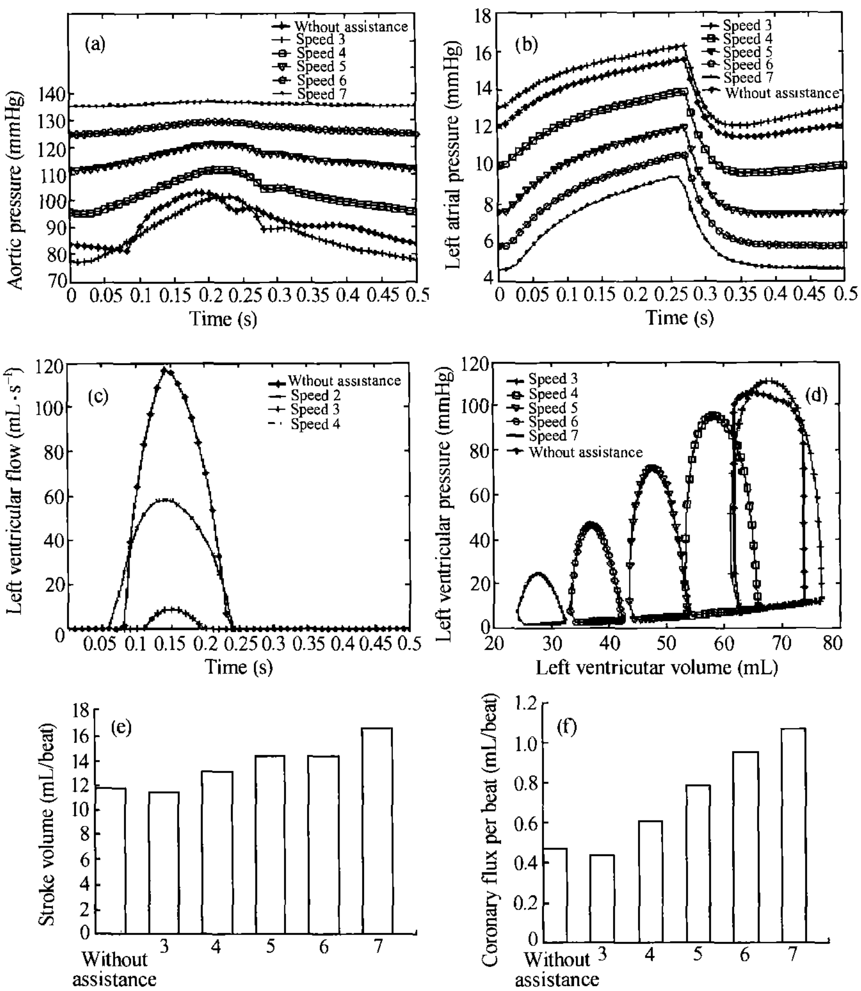


Fig. 5. Effects on cardiac parameters when the DAV operates at different speeds. (a) Aortic pressure, (b) left atrial pressure, (c) blood flux pumped out from left ventricle per beat, (d) pressure-volume relationship of left ventricle during one cardiac circulation, (e) stroke volume per beat, (f) coronary flux per beat.

A low cardiac output, low coronary flux and high left atrial pressure are the important criteria for transplantation or implantation of assist devices. And the DAV will increase the heart's stroke volume, coronary flux per beat and reduce the left atrial pressure at a reasonable rotation speed, as shown in Fig. 5 (b) and (e). Compared with a failing heart without assistance, when the DAV operated at speed 7, stroke volume increased by 30%, coronary flux per beat increased by 127% and mean left atrial pressure decreased by 51.4%.

Fig. 5(c) plots the blood flow pumped out from the left ventricle during one cardiac cycle. It is indicated that only at speeds 1—3 could the left ventricle pump out blood. When the DAV rotation speed is above 6000 r/min, the left ventricle pumps out hardly any blood.

According to Fig. 5(a)—(f), the DAV should work above speed 4. When the DAV operates below speed 4, its resistance property behaves over dynamic property, thus with the DAV implanted in the failing heart, the function of the heart even becomes worse than that without any assistance.

## 4 Discussion and conclusions

In this paper a dynamic model for the DAV has been established based on experimental data gained from the mock circulatory loop. We inserted this model into the canine circulatory system to simulate the operation of DAV in a living canine circulatory system with 30% left ventricular ischemia.

The DAV has both resistant and dynamic properties. When it operated at low rotation speeds (below speed 4), it could not help the failing heart and even made it worse, putting a bigger burden on the cardiac circulatory system.

Different from other LVAD devices, a little hysteresis was observed in the simulation. It means that the DAV is sensitive to the changes of other parameters. For example, the rotation speed of the extra-corporeal whirling magnet. Due to this property, the DAV's speed can be controlled accurately by altering the rotation speed of the extra-corporeal whirling magnet to better assist the failing heart, though this property also results in bad stability.

The DAV brings about assisting effects to improve cardiac parameters, including an increase in stroke volume, a decrease in left atrial pressure and blood pumped out by the left ventricle, an increase in mean aortic pressure, a decrease in left ventricular volume and area of the pressure-volume loop during one cardiac circulation cycle. A failing heart with different extents of left ventricular ischemia calls for different rotation speed levels. For example, when 30% left ventricle is ischemic, speed 4 should be taken at least, otherwise the DAV will cause huge backflow, decrease mean aortic pressure and stroke volume and increase left ventricular volume, area of the pressure-volume loop, left atrial pressure and blood pumped by the left ventricle. These have been proved to exacerbate regional ischemia of the failing heart.

To judge the validity of the DAV model, we compared the computation results of cardiac parameters with the *in vivo* experimental data[9] and found each variable differential was <15%. In 2002, Li et al. implanted the DAV into the aortic chamber in dogs and recorded the left ventricular pressure and aortic pressure by inserting thin tubes into the left ventricular apex and the femoral artery when the DAV operated at different speeds (Table 2). With the DAV and the canine circulatory system, we computed the left ventricular pressure and aortic pressure as well (Table 3).

Table 2. The peak systolic left ventricular and aortic pressure derived from the *in vivo* experiment when the DAV works at three rotation speeds (mmHg)

| | Speed level | | | |
|---|---|---|---|---|
| | Without assistance | 3000 r/min | 6000 r/min | 9000 r/min |
| Left ventricle | 145 ± 21 | 107 ± 24 | 74 ± 19 | 28 ± 14 |
| Aorta | 114 ± 17 | 123 ± 12 | 121 ± 15 | 126 ± 18 |

Table 3. Simulated and computed peak systolic left ventricular and aortic pressure when the DAV works at three rotation speeds with 30% left ventricular ischemia

| | Speed level | | | |
|---|---|---|---|---|
| | Without assistance | 3000 r/min | 6000 r/min | 9000 r/min |
| Left ventricle | 105.11 | 117.21 | 94.76 | 24.35 |
| Aorta | 102.95 | 88.49 | 111.68 | 136.97 |

From Tables 2 and 3, it can be seen that the simulation results are well consistent with those obtained from the *in vivo* experiment. Because we did not know the extent of ischemia in the dog' left ventricle, in simulation the Rm was set to be 30%. When the DAV operated at speeds 1—3 it was in a deviant and unstable way, so condition of the failing heart with the DAV inserted became even worse than that without assistance. When the DAV operated above speed 3, the simulated left ventricular peak pressure and aortic peak pressure had a <10% difference from those in *in vivo* experiments.

When the DAV rotation speeds up, some improvements to the cardiac variables could be achieved, for example, the left ventricular peak pressure was down to 24.35 mmHg with the DAV rotating at speed 7 and the left ventricle needs not to pump out blood with the DAV rotating above speed 4, which means that with the assistance, the muscle of the left ventricle can relax and recuperate. However, an over-high rotation speed will cause high shear stress. Therefore an optimized strategy to achieve application of the DAV in clinical patients with the lowest pump speed should be established.

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