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Energetics of the Heart Model with the Ventricular Assist Device

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= Abstract =

We investigated the energistics of the physiological heart model by comparing predictive indexes of the myocardial oxygen consumption (MOC), such as tension-time index (TTI), tension-time or force-time integral (FTI), rate-pressure product (RPP), pressure-work index, and systolic pressure-volume area (PVA) when using the electro-hydraulic left ventricular device (LVAD). We developed the model of LVAD incorporated the closed-loop cardiovascular system with a baroreceptor which can control heart rate and time-varying elastance of left and right ventricles. On considering the benefit of the LVAD, the effects of various operation modes, especially timing of assistance, were evaluated using this coupled computer model. Overall results of the computer simulation shows that our LVAD can unload the ischemic (less contractile) heart by decreasing the MOC and increasing coronary flow. Because the pump ejection at the end diastolic phase of the natural heart may increase the afterload of the left ventricle, the control scheme of our LVAD must prohibit ejecting at this time. Since the increment of coronary flow is proportional to the peak aortic pressure after ventricle contraction, the LVAD must eject immediately following the closure of the aortic valve to increase oxygen availability.

Key words : LVAD, Cardiovascular model, Computer simulation, Myocardial oxygen consumption

INTRODUCTION

Mechanical support of the failing left ventricle has been used clinically for over than 25 years in the form of steady flow pump, pulsatile left ventricular assist device (LVAD) and intra-aortic balloon pump (IABP). The goals of each device are to maintain the systemic circulation and to increase coronary perfusion while reducing the myocardial oxygen need for the recovery of the failing left ventricle. With these respect, we developed an electro-hydraulic LVAD which can operate the synchronized assist pumping with the natural heart. See Figure 1. This LVAD can control the assist volume and the delay time of the ejection with the R peak of the ECG signal, which might be a important operation especially for the weaning of the patients.

The safety and efficiency of the aortic assist pumping in failing heart caused by ischemic or post cardiotomy cardiogenic shock are well known[1]. However little is known regarding the physiological control mode of pulsatile assist pumping.

Now, our study focused on the energetic behavior of failing heart when applying an electro-hydraulic LVAD with left atrium cannulation. The computer model of the electro-hydraulic VAD was developed in this study, which consists of three parts; i) the model of DC motor with PI controller, ii) the model of hydraulic pump system which includes the blood sac, the left atrial inflow cannular, the aortic outflow graft, and two prosthetic heart valves, and iii) the model of the closed-loop cardiovascular system with a

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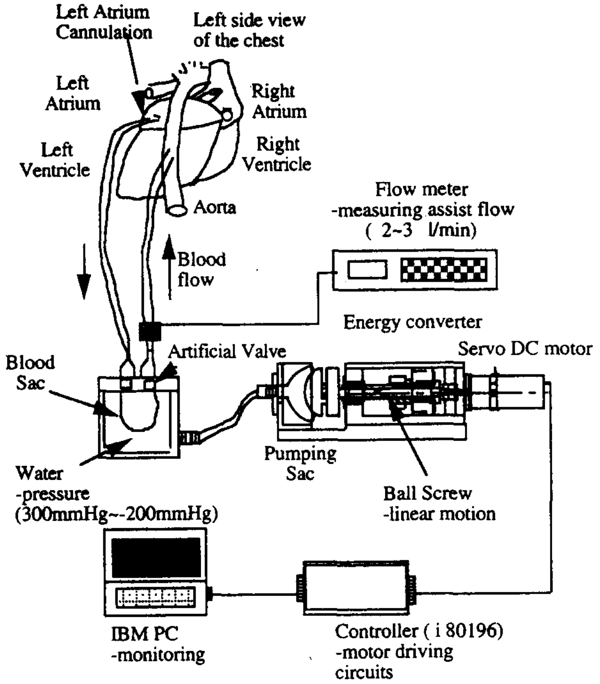


Fig. 1. Schematics of Electro-hydraulic Left Ventricular Assist Device

baroreceptor. In this cardiovascular system model, the heart rate and the elastance of the right and left ventricles were controlled physiologically[2].

There are several indexes or predictors of myocardial oxygen consumption such as tension-time index (TTI), tension-time or force-time index (FTI), rate-pressure product (RPP), pressure-work index (PWI), and systolic pressure-volume area (PVA). These parameters were evaluated through the computer model with respect to the LVAD operating conditions, especially the timing of assist ejection, considering the benefit of the left ventricular assist.

MATERIALS AND METHODS

Cardiovascular System

Many good cardiovascular system models (CVSM) were developed differently since 1970's. We made the cardiovascular system model with some modification of Rideout's[3] which is a Windkessel model composed of resistances, inductances and compliances. It has a simple baroreceptor feedback model and the controlled contractility of the ventricles. The CVSM is represented by electric symbols in Figure 2.

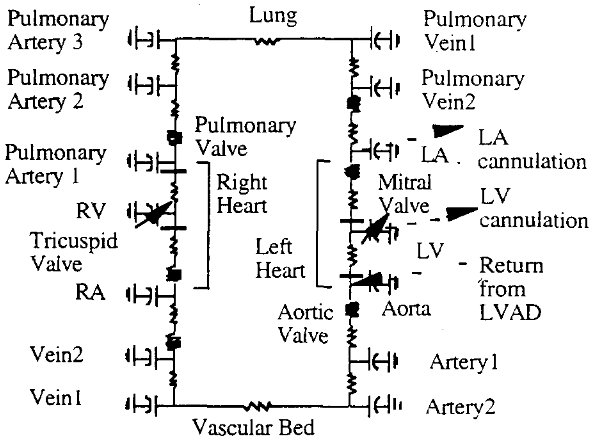


Fig. 2. Cardiovascular System Model

LVAD Modeling

In figure 3, LVAD system is presented as electrical components where the motor and pumping sac are simplified to a variable flow source, which is different from other computer models. Normally pneumatic LVAD actuator supplies the constant pressure but hydraulic LVAD, the volume with compliant pumping sac.

-Motor Control System

PI control is obtained by a micro-controller (i80196)., The velocity of motor from the encoder signal is controlled by changing the voltage with PWM (Pulse Width Modulation) technique. Each millisecond, the control values are updated.

-Hydraulic Components Model

Blood sac, chamber, inlet outlet cannular are similar to the conventional pneumatic LVAD, except that the actuating media is not air but fluid. The cannular is modeled by an inductance and a resistance. The values are calculated considering turbulent flow and tapering shape[11,12]. The artificial valve is treated as an ideal diode and a pressure varying orifice resistance which makes the pressure drop proportional to the square of flow[13]. The compliance and the effective area of pumping sac were determined experimentally.

Numerical Solving Method

More than 54 differential equations were solved by

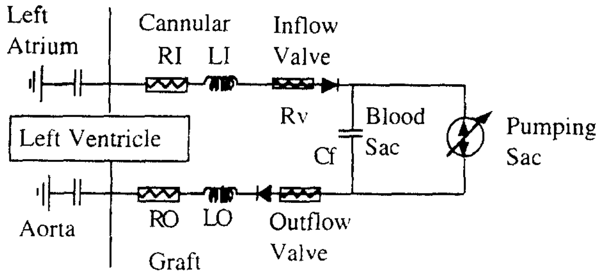


Fig. 3. Electro-hydraulic LVAD Model

4th order Runge-Kutta method with 1 ms time interval using C language in 486 PC.

Myocardial Oxygen availability

Assessing myocardial oxygen availability, we calculated the total coronary flow (TCF) per heart beat. The stenosis of coronary vessel was characterized by setting resistance to 10 mmHg*sec/ml[4, 5].

Myocardial Oxygen consumption

The effect of pulsatile or continuos flow LVAD on left ventricular myocardial oxygen consumption and regional organ blood flow was investigated by many researchers[6, 7]. But not much was known about the interaction between natural heart and the artificial pump due to the difficulties of such experiment. To estimate the myocardial oxygen consumption, several parameters are incorporated in computer model[8] as follows.

-LV Contractility

Emax is the slope of ESPVR(end-systolic pressure-volume relation) as a load-independent index of contractility. Vo is the volume intercept of an ESPVR.

-Tension-Time Index (TTI) and Diastolic-Pressure Time Integral (DPTI)

The area under the systolic and diastolic portion of the aortic pressure graph.

-Force-Time Integral (FTI)

Force-time integral is the time integral of total ventricular wall force through one cardiac cycle.

$F = 1.36 \times P \times A = 1.64 \times P \times V^{2/3}$

P : ventricular pressure(mmHg)

A : lumen cross-sectional area(㎠)

-Rate-Pressure Product (RPP)

Rate-Pressure product is left ventricular systolic pressure multiplied by heart rate.

-Pressure-Volume Area (PVA)

PVA is an area bounded by the ESPVR, the EDPVR and the systolic pressure-volume trajectory of each beat. Much studies concerning PVA have been done by Suga[10].

$MVO_2 = A \times PVA + B \times Emax + C$

MVO_2 : Myocardial oxygen consumption[ml/min/100g]

A =1.8x10-5 B=0.0024 C=0.0014

$MVO_2 = A \times PVA \times HR + B \times Emax \times HR + C \times HR$[ml/min/100g]

-Pressure-Work Index (PWI)

PWI in milliliters of O_2 per minute per 100g was calculated according to the modified formula proposed by Rooke and Feigl[9] as

$MVO_2 = K_1(SBP \times HR) + K_2\ \{(0.8SBP + 0.2DBP) \times HR \times SV\} + 1.43$
BW

SBP : systolic blood pressure(mmHg)

DBP : diastolic blood pressure(mmHg)

HR : heart rate(beat/min)

SV : stroke volume(ml) BW : body weight(㎏)

K_1 : 4.08 × 10-4 K_2 : 3.25 × 10-4

Computer Simulation

To simulate failing state of heart, we decrease the coefficient of the ventricular contractility from 1 (normal state) to 0.5 (failing state). We evaluated each indexes in computer model, which represent the various energetics of the heart according to the variation effect of delay time for the assist flow, with the fixed heart rate of 75 bpm. LVAD model operated synchronously with heart beat by adjusting the systolic and diastolic velocity of the LVAD motor.

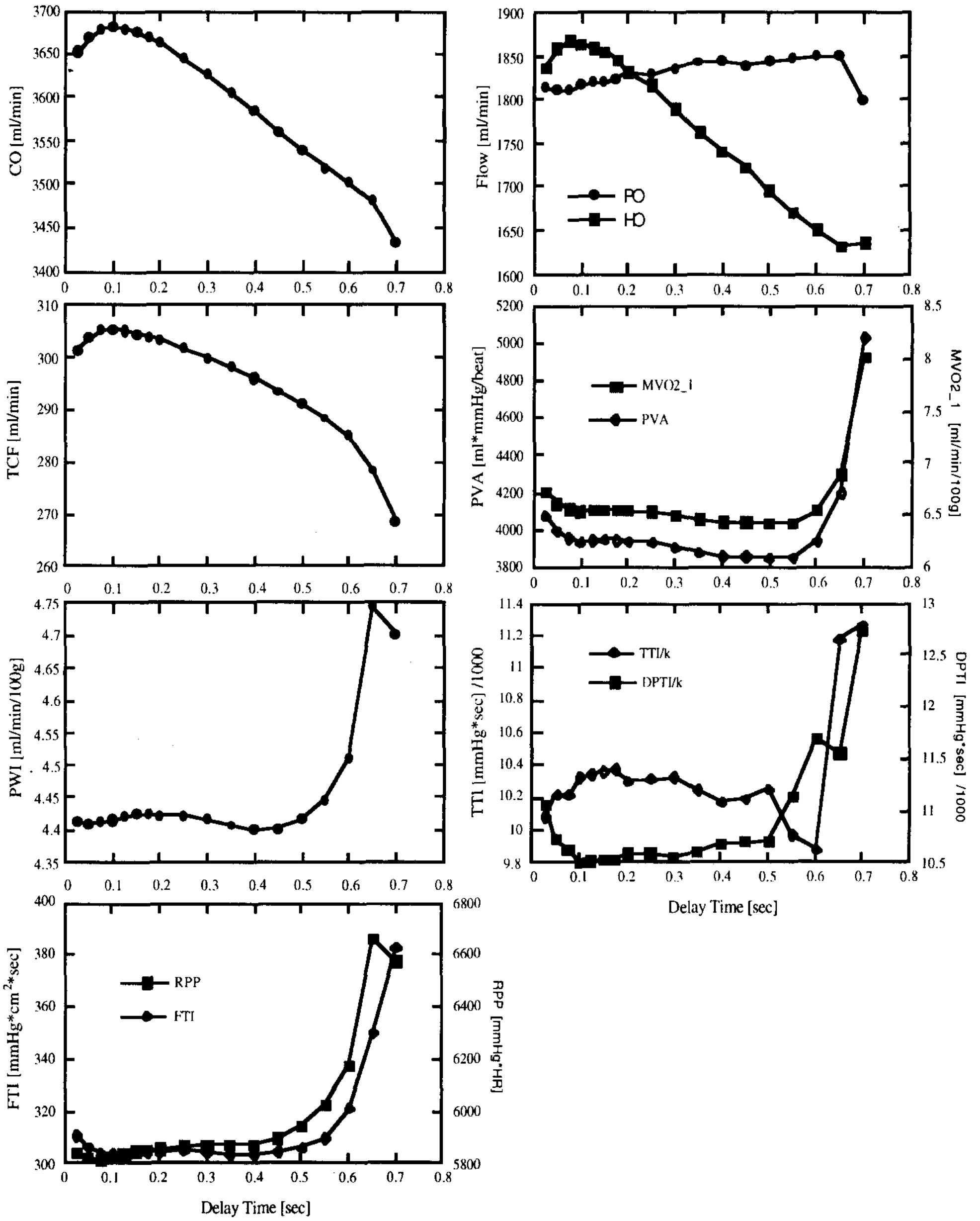


Fig. 4. Total Cardiac Output (CO), Pump Output (PO), Total Coronary Flow (TCF), Pressure Volume Area (PVA), estimated Myocardial Oxygen Consumption (MVO2-1) from PVA, Pressure Work Index (PWI), Tnesion Time Index (TTI), Diastolic Pressure Time Integral (DPTI), Force Time Integral (FTI), and Rate Pulse Product (RPP) vs Delay Time

RESULTS

Figure 4 shows the overall result from the simulation. The delay time of assist ejection around 0.1 second produces maximum cardiac output. With increasing the delay time, LVAD takes the place of the natural heart inefficiently. That means little increase in pump output and much decrease in heart output. The maximum of total coronary flow matches with 0.1 second delay time. PVA and MVO_2 decrease slightly and increase in steep curve after 0.6 delay time. PWI shows similar results to PVA. There are the opposite characteristics of TTI and DPTI until 0.6 second. But much delay time augments both of them. FTI and RPP also increase dramatically after 0.5 second. Dif-

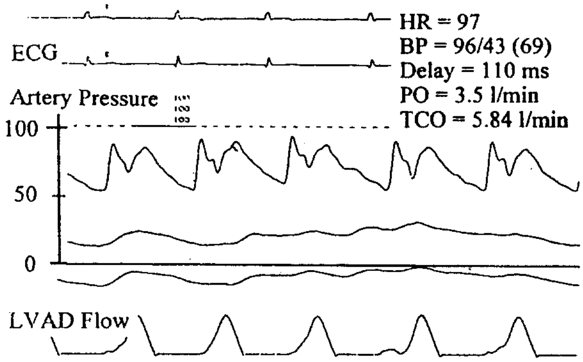
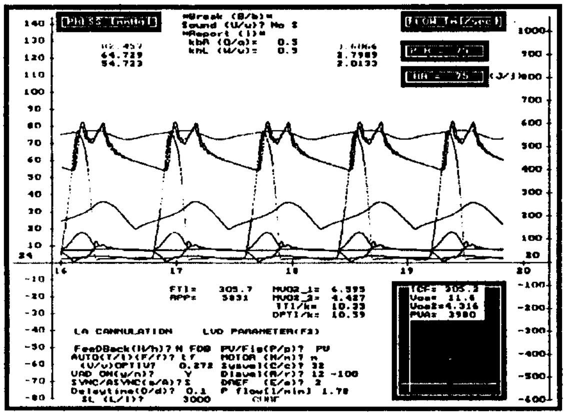


Fig. 5. The pressure Wave forms in Animal Experiment



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*Break (B/b)*
Sound (U/u)? No S
*Report (I)*
 kbA (Q/q)=   0.5
 kbL (W/w)=   0.5

FTI=    305.7    MVO2_1=  6.595
APP=     3831    MVO2_2=  4.427
                  TTI/k=  10.33
                 DPTI/k=  10.59

TCF= 305.2
Vos=  11.6
Vos2=4.316
PVA=  3980

LA CANNULATION      LVD PARAMETER(F2)

FeeDBack(N/n)? N F00  PV/Fig(P/p)?  PV
AUTO(T/t)(F/f)? tf    MOTOR (M/m)? n
  (V/v)OPTIU?   0.272 Sysvel(C/c)? 32
VAD ON(y/n)?     Y    Diavel(A/r)? 12 -100
SYNC/ASYNC(s/A)?S     DREF  (E/e)?  2
Delaytime(D/d)?  0.1  P flow[l/min] 1.78
  SL (L/l)?      3000
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Fig. 6. The Simulation Program

ferent indexes show the similar tendency with varying delay time. Typical trends of the pressure is that shorter delay time makes higher peak in aortic pressure.

The optimal delay time of this LVAD is expected around 0.1 second after the R peak of ECG. It can supply the maximum systemic circulation and the maximum coronary flow with relatively small myocardial oxygen consumption.

Figure 5 shows waveforms of the aortic pressure and LVAD assist flow during the animal experiment. A hardcopy of the monitor program is shown in Figure 6. Aortic pressure wave has much likelihood between computer model and animal experiment data. It would support the validity of the simulation study in cardiovascular system.

SUMMARY AND CONCLUSION

It is presumed that by using LVAD, sustaining the circulation and augmenting the coronary flow will provide a chance for a reversible myocardial injury to recover while minimizing the myocardial oxygen consumption.

In this paper we optimized the assist ejection time of the electro-hydraulic LVAD for the case of left atrium-aorta bypass and investigated the myocardial oxygen consumption by evaluating the various indexes in computer model. The dependency of LVAD control mode concerning delay time of assist ejection determined 1) fully counter pulsation; much delay time increases the afterload of the heart in next systolic phase and the myocardial oxygen consumption which represents the work load of the natural heart. 2) the total coronary flow per beat is strongly influenced by the peak aortic pressure in diastole phase of the ventricle. 3) the assist ejection should be started just after the aortic valve closure. Whereas IABP prefers the counterpulsation in late diastole of the heart reducing the afterload of systole by deflation, pulsatile LVAD must not add the extra afterload by end-diastolic ejection.

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