Inflow Mechanism of the Double-membrane Electromechanical Total Artificial Heart

In Young Kim, Jong Won Kim, Sang Hun Lee,
Byoung Goo Min

Dept. of Biomedical Engineering
College of Medicine
Seoul National University

I. Introduction

We have developed a new electroemchanical total artificial heart(TAH). In this artificial heart, a pendulum-type actuator reciprocates around the shaft fixed to outer housing and then left & right sacs are ejected alternatively, where these sacs have a double membrane. [1,2] Since the outer membrane is attached to the actuator, the suction pressure of the ventricle fabricated with double membrane is smaller than that of the single membrane attached case due to compliant air volume between double membranes. The size of the left ventricle in our pump is larger than that of the right ventricle by 10% to diminish the imbalance problem of the electrical TAH, that is larger output of the left ventricle to 7 % or 8 %. This difference of the output between the left ventricle and the right ventricle is sufficient to maintain the LAP level below 15mmHg.[3] And these ventricles are actively filled during diastolic phase. But the air between double membrane could also disturb the imbalance operation of the TAH due to the compliance property of air between double membranes and then the output of ventricles is also dependent on it.

We have tried to find the appropriate design of electromechanical TAH to provide adequate suction pressures of each ventricles during diastolic phases and to control imbalance problem. But since inflow mechanism in our pump is very complicated and the experimental approach using mock circulatory system to understand the relationship bewteen internal volume and pressure of each chamber is difficult, we have studied the inflow mechanism by computer simulation with some appropriate physical assumptions about our pump.

To understand inflow mechanism in our pump gives important information about design criteria for the appropriate condition to solve the suction problem and the imbalnace problem of the electrical TAH.

II. Theoretical background

The following statements can be assumed when the pendulum type atuator reciprocates to eject each ventricle alternatively.

1. Changes of both ventricular pressures are related to pressure changes between double membranes as follows;

$$\dot{P}rv = (Pbr - Prv) \times K1 \quad \text{------------ (1-a)}$$

$$\dot{P}lv = (Pbl - Plv) \times K1 \quad \text{------------ (1-b)}$$

2. The air between double membranes and variable volume air is governed by the ideal gas law as follows;

$$Pbr \times Vbr = Cbr \quad \text{------------ (2-a)}$$

$$Pbl \times Vbl = Cbl \quad \text{------------ (2-b)}$$

$$Pvv \times Vvv = Cvv \quad \text{------------ (2-c)}$$

3. The sum of the right(or left) ventricular volume and the air volume between right(or left) side double membrane changes according to the given velocity profile of the actuator and pressure difference between variable voulme and the air in double membrane such as eq.s (3-a) and (3-b).

$$\dot{V}br + \dot{V}rv = Qr = Gvpr + (Pbr - Pvv) \times K2 \quad \text{----- (3-a)}$$

$$\dot{V}bl + \dot{V}lv = Ql = Gvpl + (Pbl - Pvv) \times K2 \quad \text{----- (3-b)}$$

And Gvp and Gvp are assumed to be gaussian functions.

4. Volume flow rate of inflow (or outflow) is propotional to the difference between ventricular pressure and the atrial (or arterial) pressure as follows;

$$\dot{V}rv = (Pra - Prv) / R$$
(right ventricular diastolic phase) (4-a)

$\dot{V}lv = (Pla - Plv) / R$
(left ventricular diastolic phase) (4-b)

$\dot{V}rv = - (Plv - Ppa) / R$
(right ventricular systolic phase) (4-c)

Futhermore, the effect of the valvular regurgitation can be included by adding a backflow term which is propotional to the difference between left ventricular pressure and LAP such as the eq. (4-d) at the left ventricular systolic phase.

$$\dot{V}lv = - (Plv - Pao) / R + (Pao - Plv) \times K3 \quad (4\text{-}d)$$

5 . Variation of the total pump volume is propotional to the variable volume pressure due to compliance of the polyurethane pump's housing.

$$\dot{V}tot = (Pvv - Po) \times K4 \quad (5)$$

6 . The left ventricular cardiac output becomes larger than that of the right because of the larger outflow volume rate which is induced by the velocity profile of the actuator at the left systolic phase by 10%.

Using above assumptions and appropriate values of the coefficients in above equations, we performed computer simulation about the inflow mechanism of the pendulum type moving-actuator total artificial heart.

Parameters shown above equaitons are summarized in table 1 and the schematic diagram of the pendulum type pump is shown in fig. 1.

III. Computer Simulation

Computer simulation were performed on a IBM PC-386 with appropriate values of coefficients in the theoretical model shown in table 2 and above governing equations. The flow chart of the simulation are shown in fig.2.

In the simulation, we calculated stroke volumes of the left and right ventricles and difference between them at the given outflow volume rates(Gvpr & Gvpl) and values of the coefficients according to the various air volumes the between double membranes in order to find the maximum stroke volume, while maintaining imbalanced cardiac output by 10% of the left stroke volume.

IV. Results

Throughout the computer simulation, we know that the air volume size of 10 cc in left side double membrane and 6 cc in right side makes maximal cardiac output of 63.4 cc and maintain different cardiac outputs of 8 cc between left and right sacs which could maintain the LAP level below 15mmHg, that is similar to the case of the natural heart.

Figure 4 shows the calculated changes of volumes and pressures of the five sections for our pump and the measured changes of pressures are shown in figure 4 and its waveforms are very similar to those in fig. 3.

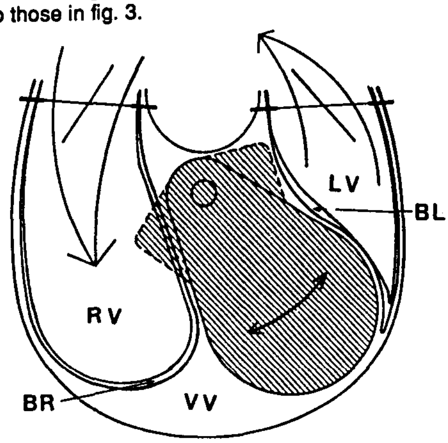

Figure1. Schematic diagram of pendulum type TAH (RV : right ventricle, LV : left ventricle BR , BL: right & left voulme between double membrane. VV : variable volume)

Vvv Pvv	: voulme and pressure of variable volume
Vtot	: total pump volume
Vbr,l Pbr,l	: voulme and pressure of the air between right, left double membrane
Vr,lv Pr,lv	: volume and pressure of right, left ventricle
Pr,la	: pressure of right, left atrium
Ppa	: pumonary arterial pressure
Pao	: aortic pressure
Po	: atmospheric pressure
R	: valvular resistance
Gvpr,l	: right, left gaussian volume change profile
Cbr,l ,Cvv, K1,2,3,4	: contants

Table 1. Nomenclature of equations

K1	:	30 sec^{-1}
K2	:	0.1 ml / mmHg / sec
K3	:	0.1 ml / mmHg / sec
K4	:	0.4 ml / mmHg / sec
R	:	0.15 mmHg / ml / sec

Table 2. Values of coefficients and contants

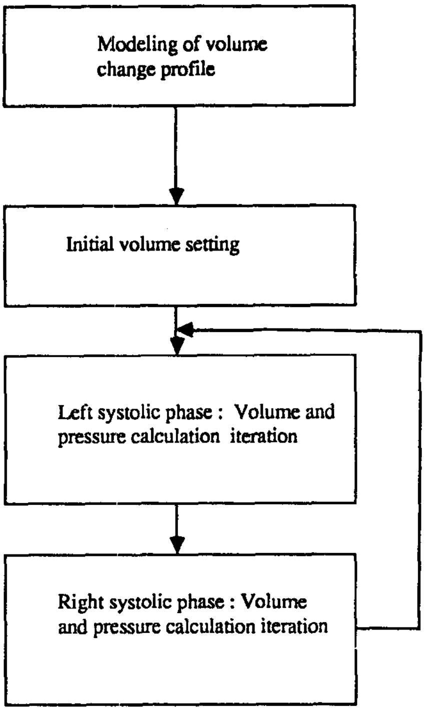

Figure 2.
The flow chart of the computer silmuation

V. Discussion

In our physical model, the total pump volume is modeled to vary according to the actuator's movement due to compliance of the polyurethane pump's housing. But the implanted TAH will become incompliant by tissue encapsulation over the pump. So our optimal air volume between double membrane may be corrected for the imbalance of implanted pump operation.

Our model is based upon the natural heart in steady state of fixed AoP & PAP & LAP & RAP. In real case, the circulatory system of the human also varys and the these four pressures are varied.

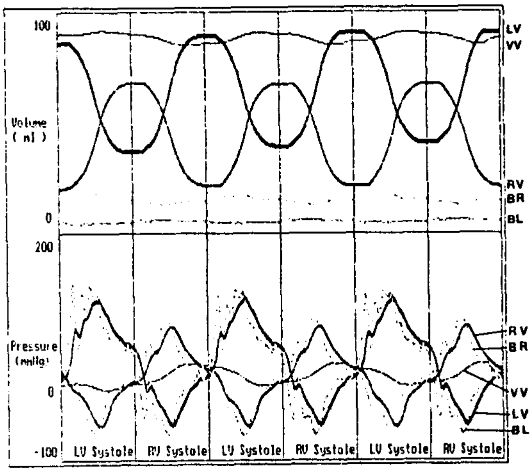

Figure 3.
Waveforms of volumes and pressures of five sections of the pump calculated from the computer simulation

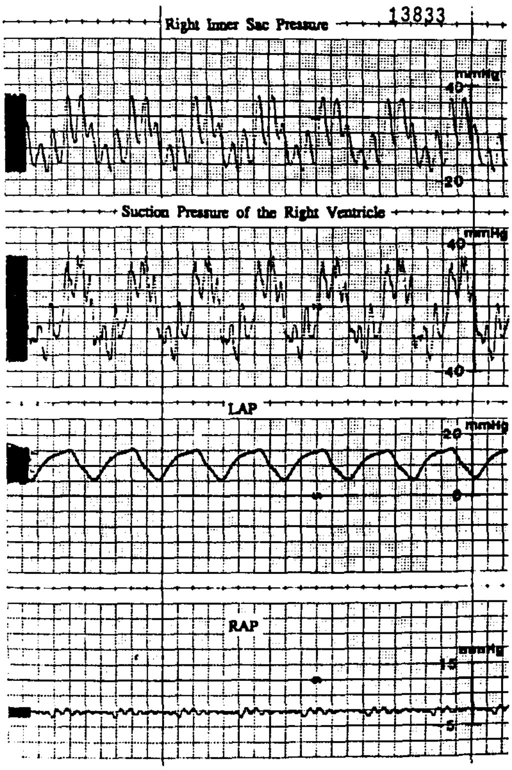

Figure 4.
Waveforms of LAP, RAP, suction pressure and the right ventricular pressure measured from the mock circulatory test

Therefore, the circulatory system model also is needed to study the dynamic response of our pump with four pressures which we assumed vary slowly, or contant values.

Comparisions of the above results to the mock circulatory test are needed to provide optimal cardiac output of the.pump.

Referrences

[1] Min BG, Kim HC, et al.; Amoving actuator type electromechanical total artificial heart - Part I : Linear type and mock circulation experiments. IEEE Trans., in publishing.

[2] Min BG, Kim HC, et al. ; Invitro and invivo evaluation of a new smoving-actuator type electromechanical total artificial heart - Part II : Circular type and animal Experiments. IEEE Trans. , in publishing.

[3] Olsen DB, Long JW ; Simplified right-left balance for the implanted heart, Proceedings of the 3rd international symposium on current ststus of completely implantable artificial heart, (Eds) Tetsuyo Akutsu, Springer-Verlag, Tokyo, Nov. 1990.