심혈관계 컴퓨터 모델의 유효성 연구

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Validity of Computer Model of Cardiovascular System

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Introduction

A versatile computer simulation of the cardiovascular system was developed. The objectives of the simulation was to present the validity of the computer model when developing the cardiac assist devices (e.g. Intra Aortic Balloon Pump (IABP), Left Ventricular Assist Device (LVAD), Total Artificial Heat (TAH) and etc.). The computer model studies can provide a desirable control strategies by predicting the response of the circulation to mechanical perturbation of left ventricular and biventricular assistance.

In this study, two different simulations were performed for the practical applications. First, for the implantation of TAH we have tried the surface-induced deep hypothermia method incorporated with biventricular assist device (BVAD) without total cardiopulmonary bypass machine so called heart-lung machine. The feasibility of this operation technique was studied by using the computer model of the circulatory system. Second, a method for indirect and real-time estimation of cardiac output of the circulatory system by LVAD was tested. The parameter estimation technique is useful for clinical application of the LVAD since it needs only two measurement : the outflow rate of blood from the LVAD and the aortic pressure.

Simulation of BVAD and TAH with failing heart

Methods

Many good cardiovascular system models (CVSM) were developed differently since 70's. We made the cardiovascular system model with some modification of Rideout's which is a Windkessel model, i.e. a network 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 Fig 1. BVAD model of the controller and hydraulic parts and simple TAH model were added to CVSM. TAH model was assumed to generate the sinusoidal blood flows of the artificial ventricles.

In the operation of TAH implantation, as the body temperature drops below 30 centigrade by the surface cooling, natural heart starts fibrillation then stops beating.

The simulation procedure is as follows. To simulate the hypothermia state of heart, we decrease the coefficient of the ventricular contractility from 1 (normal state) to 0 (failing state) gradually. At the same time BVAD control parameters were adjusted to supply the blood to the circulatory system. Finally we change the pumping device from BVAD to TAH on behalf of natural heart.

The aortic pressure for the body perfusion and the left atrium pressure for prevention of pulmonary edema were investigated carefully in real-time simulation.

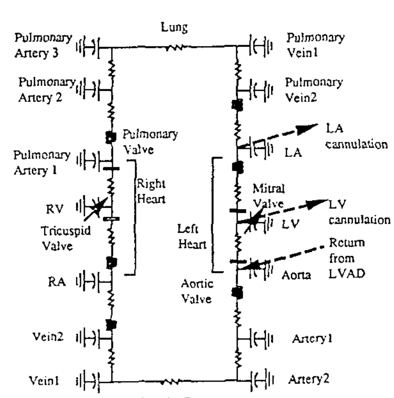

Fig.1 Cardiovascular Model

Results

In all simulation the effect of baroreceptor feedback was not applied to CVSM. Fig. 2 shows the normal state of the heart. After decreasing the heart contractility, BVAD started the operation with the assist flow around 2 l/min. We adjusted the control parameters of BVAD such as Stroke Length (SL), systole and diastole velocities. See Fig. 3. In Fig. 4 the TAH can make the reasonable blood pressures to support the perfusion need for the circulatory system.

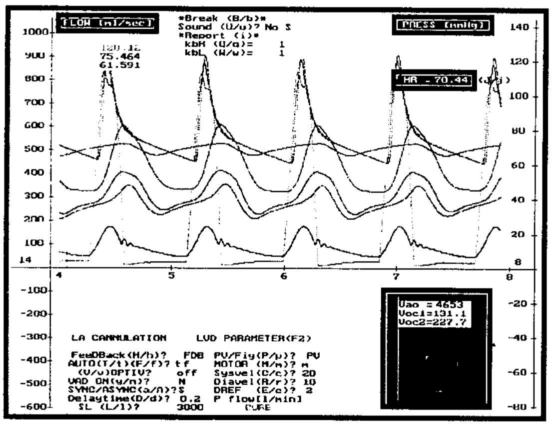

Fig. 2 Normal state of the heart

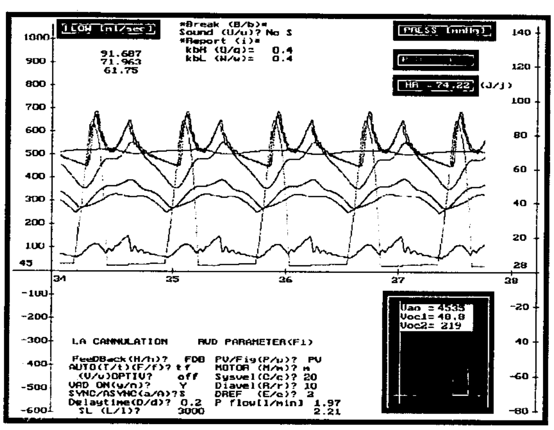

Fig. 3 Operation of BVAD with the failing heart

Simulation of parameter estimation application in LVAD

Methods

Let us introduce electrical circuit model of the circulatory system assisted by the LVAD into the present modelling as shown in Fig.5. The autoregressive model was used to describe the circulatory model. The parameters of the model were estimated by the recursive least square method.

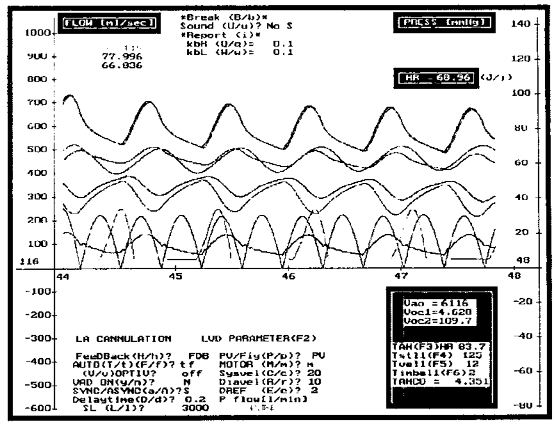

Fig. 4 Operation of TAH

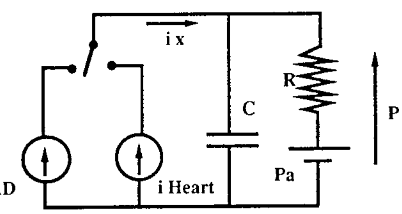

Fig. 5 Electrical model of the arterial part of the circulatory system

The differential equation of model can be given by

$$\dot{p}(t) = -\tau^{-1}p(t) + C^{-1}i_x(t-D) + \tau^{-1}P_A \qquad (1)$$

where τ = CR and D[s] is a time delay between $i_x(t)$ and p(t)

The time series model (ARMAX model) of the system can be represented by

$$p_k = \alpha\, p_{k-1} + \beta\, i_k + \gamma + \omega_k \qquad (2)$$

where

$$d = D/h \text{ (an integer)}$$

$$\alpha = e^{-h/\tau}$$

$$\beta = (1 - e^{-h/\tau})R$$

$$\gamma = (1 - e^{-h/\tau})P_A$$

and where ω_k represents the modelling or measurement error.

Letting

$$\theta = [\ \alpha, \beta, \gamma\ ]^T$$

$$\omega_k = [\ p_{k-1}, i_{Xk-1}, 1\ ]^T$$

$$\Omega = [\ \omega_d, \omega_{d+1}, \cdots, \omega_{d+k}\ ]^T$$

$$\eta = [p_d, p_{d+1}, \cdots, p_{d+k}]^T$$

yields the identified value $\hat{\theta}$ of the coefficient parameter vector θ as

$$\hat{\theta} = [\Omega^T \Omega]^{-1} \Omega^T \eta \qquad (3)$$

By computer simulation, the validity of this method was evaluated. Acquiring the pressure and flow signals from aortic component, each parameter value is obtained from Eq. 3. And then the pressure signal ,when heart ejaculates, is used to estimate the flow of heart.

Results

If the pressure and flow signals are acquired at the same site of the circulatory system, this method can estimate the cardiac output almost correctly. See Fig.6 But in clinical situation it is impossible to implant the flow-meter for long period. Therefor the use of this method seems difficult at present state of technical development

Discussion

In summary, this simulation predicts pressure and flow waveforms for the normal and failing circulation with and without BVAD or TAH. It is clear that the model cannot count for variability among different animals. Thus, absolute values may differ for model and experiment. Rather than simulating absolute values of system parameters, the model is expected to provide a better indication of changes in cardiovascular system due to mechanical perturbations. The computer model permits easy variation of parameters of both the cardiovascular system and the circulatory device, enabling the testing of control strategies in different states of the circulation. Using the computer model, control strategies of BVAD or TAH may be tested and studied prior to the construction of a prototype and the surgical operation. procedure. In addition, use of the model reduce the number of required animal experiments.

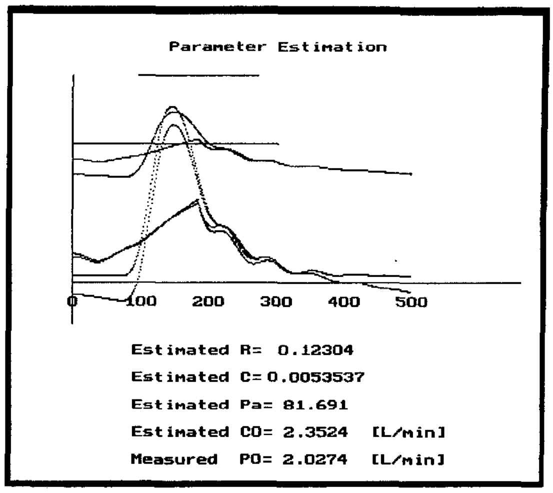

Fig. 6 Parameter estimation result

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