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Computational study of the hemodynamics of the patients after the Fontan procedure

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Fontan 시술 이후 환자의 혈류역학적 상태에 대한 수치적 연구

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Key Words : Fontan procedure, Hemodynamics, Lumped parameter model, Control mechanisms

Abstract

In this study, the computational method is presented to simulate the hemodynamics of the patients after the Fontan procedure. The short-term feedback control models are implemented to assess the hemodynamic responses of the patients exposed to the stresses such as gravitational effect or hemorrhage. To construct the base line of the Fontan model, we assume an increase in venous tone, in heart rates, and in systemic resistance that are based on the clinical observations. For the verification of the present method we simulate the LBNP (lower body negative pressure) test for the normal and the Fontan model and we compare these with experimental data. Computational results show that the diastolic ABP(arterial blood pressure) increases but the systolic ABP decreases during LBNP. The increase in heart rate is due to the control system activated by the decreased mean ABP and CVP(central venous pressure). In case of the Fontan model, the increased venous tone is the reason of the diminished CVP change during LBNP. We also simulate 20% hemorrhage stress to the patient after the Fontan procedure and these results are compared with the experimental and the existing computational one. Computational results on the hemodynamics of patients after the Fontan procedure show that the mean ABP and cardiac output decrease. Heart rate and systemic resistance increase to compensate for the decrease in ABP. The sensitivity analysis according to the conduit resistance is also presented to delineate the effects of the local blood flow resistance. The cardiac output decreases according to the increase of the conduit resistance. The 50% increase in the conduit resistance causes about 3% decrease of cardiac output.

1. Introduction

Fontan procedure was originally proposed for the patients with tricuspid atresia[1]. Since then, the Fontan procedure has been used in a variety of cardiac malfunctions, with a low risk of mortality and significant clinical improvement[2]. There are two types in the Fontan operation: ‘cavopulmonary type’ and ‘atriopulmonary type’. The former has the flow path from vena-cava directly to pulmonary artery whereas the blood passes through the right atrium with only right ventricle bypassed in the latter type. In this study the atripulmonary type is considered for the computational study of the Fontan procedure.

Many clinical experiments have been done on the hemodynamics of patients after the Fontan procedure, but there have been only a few published computational studies[3, 4]. Pennati et al.[3] have developed the computer model to represent the homodynamics in the patient after the cavopulmonary procedure. They provided the detailed numerical results on the systemic and pulmonary circulation, but their model included no control system that seems to be considered as an essential part of the hemodynamics of the patients. Especially the amount of cardiac output in the patients

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after the Fontan procedure is not enough to sustain the need of blood supply during exercise or in case of exposure to the harzardous environments such as cold stress, heat stress, and hemorrhage. In such cases the short-term control system plays an important role in the regulation of circulation. The computational modeling suggested by Rydberg et al.[4] has been based on the fluid line model[5] using the 1-D method of characteristics (MOC). Though their model has produced reasonable results, any verification studies of the method has not been provided and they utilized non-physiological approaches for the control system in the sense that only the levels of systemic and lung resistance were controlled. No heart rate control, no heart contractility and no venous tone control were not used in their model. However, the hemodynamic change of the patients after the Fontan procedure is greatly affected by heart rate, heart contractility and venous tone modulated by autonomous nerve system.

In this study we implement the computational model to assess the hemodynamics of the patients after the Fontan procedure. We use the lumped parameter model with six compartments as the work done by Davis[6]. This model represents left and right heart, systemic arteries and veins, and pulmonary arteries and veins as linearly capacitative compartments connected by linearly resistive conduits. The mechanical properties of the cardiovascular system are modulated by feedback control mechanisms, implemented here using two major pathways. One is the baroreflex loop for control of arterial pressure, and the other is the cardiopulmonary reflex which controls circulatory blood volume. Both loops influence peripheral resistance and venous tone, as well as cardiac function[7].

2. Hemodynamic model

2.1 Normal hemodynamic model

We utilize a lumped parameter model to simulate the cardiovascular system. In normal case, the heart and circulation are represented in terms of electric circuit analogue which consists of six compartments: the left ventricle, the systemic arteries, the systemic veins, the right ventricle, the pulmonary arteries, and the pulmonary veins (Figure 1). The elements of the right heart are similar to those of the left heart. The pumping action of the heart is modeled by time varying ventricular compliance. For the normal case, the function of atrium is not explicitly modeled, its effect, however, is partially absorbed into the function of adjacent compartments. Diodes ensure unidirectional flow. Each compartment is characterized by an inflow resistance R with a unit of peripheral resistance units (PRU, mmHg·s/ml), a compliance C with a unit of ml/mmHg, a volume at zero transmural pressure V_0 (zero pressure filling volume, ZPFV) with a unit of ml, and an outflow resistance. Transmural pressure across the pulmonary capacitances varies according to intra-thoracic.

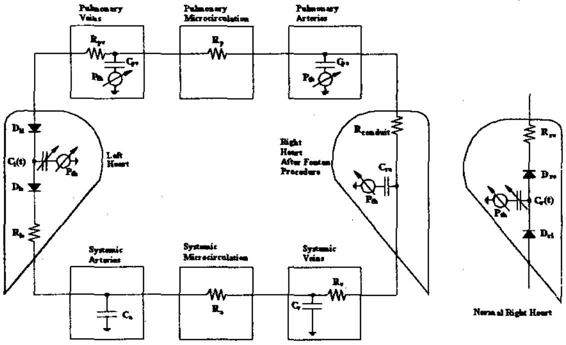


Fig. 1 Schematic of a lumped parameter model of the circulation after the Fontan procedure.

Application of Kirchhoff's law to the lumped parameter hemodynamic model leads to a matrix eqaution of the form:

$$dp/dt = Ap + b \tag{1}$$

Here p is the vector of compartmental pressures, A represents the time constants for exchange between compartments, and b is the input to the system.

2.2 Hemodynamic model of the Fontan patients

In case the Fontan procedure, some modifications should be made in the normal model. Since there is no right ventricular function and it is well known that the right atrium plays an important roles for the hemodynamics of the cardiovascular system of the patients after the atrio-pulmonary bypass surgery, we model the right heart as the right atrium compartment (Fig. 1). Some flow resistance due to the bypass graft is assumed between the right atrium and the pulmonary arteries. The hemodynamics of the patients after the Fontan procedure shows some different characteristics compared with normal subjects. To construct the baseline state of the Fontan model, we change the hemodyanmic parameters according to the clinical observations. We explain the following issues considered in this model for the Fontan patients.

(a) Increased venous tone:

To explain the increased venous tone after the Fontan procedure, we decrease the venous capacitance. Kelly et al.[8] observed about 33% decreases in forearm venous capacitance of the patients after the Fontan procedure. On the basis of this data, we assumed the same amount of decrease in overall venous capacitance after the Fontan procedure.

(b) Increased heart rate:

According to the clinical observations done by Kelley et al.[8], the heart rate in case of Fontan subjects increases compared with that of normal subjects by 3.2% - 33% (average 18%). In this study we use 82 beats/min of heart rate increased by 18% compared with the normal value of the heart rate, 72 beats/min.

(c) Increased systemic resistance:

Increase in systemic resistance for the patients after the Fontan procedure is well recognized and is also accounted in this study. We assume the 20% increase in systemic resistance in case of Fontan model. This value is also based on the clinical data proposed by Shachar et al.[9].

(d) The parameters on right atrium:

The role of right atrium is more important in case of Fontan model than in the normal model. Since the effects are, however, not delineated, we used only the normal atrium data as in the work of Ursino [10]. The capacitance and ZPFV(zero pressure filling volume) of the right atrium is considered as 31.3 ml/mmHg and 25 ml, respectively.

(e) The flow resistance due to the conduit connecting the right atrium with the pulmonary artery:

The resistance values can be changed depending on the numerous factors such as the bypass path, the existence of occlusion or thrombosis, and the state of a patient, etc. So it is very hard to define the standard value of the resistance. According to the clinical data of Shachar et al.[9], the pressure drop across the conduit is in the range of 0.3 – 4.3 mmHg (average 2.3 mmHg). We assume the pressure drop of 2.3 mmHg across the conduit. Parametric study according to the variation of the value range is also conducted in this study.

3. Control system

The mechanical properties of the cardiovascular system are modulated by feedback control mechanisms, implemented here using two major pathways. One is the baroreflex loop for control of arterial pressure, and the other is the cardiopulmonary reflex which controls circulatory blood volume. Both loops influence peripheral resistance and venous tone, as well as cardiac function as shown in Fig. 2.

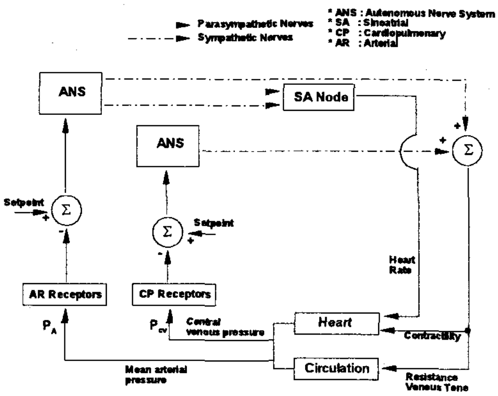


Figure 2. Schematic of the control system in the model.

4. Results and discussions

For the comparison with the existing data we compute the hemodynamics of cardiovascular system for the normal subjects and also the hemodynamic characteristics of the patients after the Fontan procedure. We provide the results of lower body negative pressure (LBNP) for the normal and the Fontan model. The effects of the hemorrhage stress are also delineated to verify the capability of the present method in simulating the hemodynamic state of the patients exposed to the hazardous environments. The sensitivity analysis according to the resistance of the bypass shunt is made to assess the effects of the local flow resistance on the overall hemodynamics of cardiovascular system of the patients after the Fontan procedure.

4.1 Computational model of the patients after the Fontan procedure

Kelly et al.[8] have delineated the hemodynamic differences between the normal subjects group and the patients group after the Fontan procedure. Of course two groups are similar in average body weight and average age. They found that the increased venous tone (decreased venous capacitance) for the patients group might be the cause of the impaired cardiac output after the Fontan procedure. The proposed decrease of the venous capacitance in their study is about 33% in forearm. So we assume 33% decrease in the overall venous capacitance. The base line value of heart rate in the Fontan model is increased by 10 beats/min that is based on the clinical observation done by Kelley et al.[8].

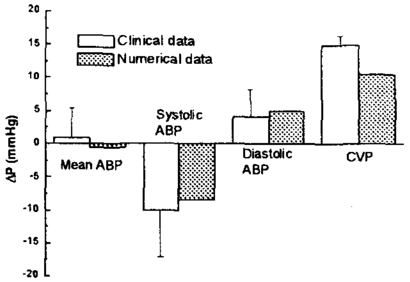


Figure 3. Comparison of hemodynamic changes between the normal and the subject after the Fontan procedure. In here $\Delta(\bullet) = (\bullet)_{Fontan} - (\bullet)_{normal}$ and HR, ABP, CVP represent heart rate, arterial blood pressure, and central venous pressure, respectively.

The flow resistance due to bypass conduit (or pressure drop through the conduit) depends on the fluid dynamical state through the shunt and the flow pathway of the Fontan operation, etc. According to the research done by Shachar et al.[9], the pressure drop through the conduit is about 0.3 – 4.3 mmHg (average 2.3 mmHg). We assumed that the pressure drop due to the conduit resistance is about 2.3 mmHg. The clinical and numerical results are described in Figure 3.

4.2 LBNP simulation for normal subject and the patients after the Fontan procedure

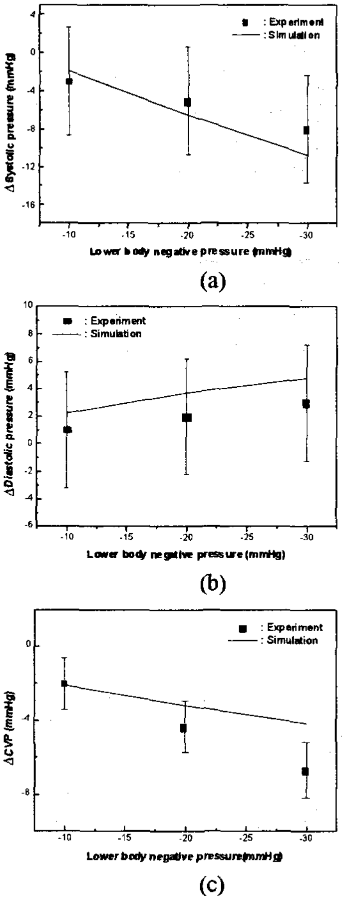
Lower body negative pressure (LBNP) loadings are tested to verify the present numerical code. LBNP is widely used for comparison and validation of cardiovascular control model because of its simplicity and availability of numerous experimental data [7,10].

External pressure applied to the lower body is simulated by specifying the bias pressures across the lower body compartment P_{bias} according to the following expression.

$$P_{bias} = \varepsilon P_{lbnp} \qquad (1)$$

Here P_{lbnp} denotes the maximum external pressure applied to the lower limbs and ε is an "attenuation" factor to take into account that only one venous compartment is used in this model. The calculated value of ε is 0.4 in this study. We also assume the leakage of blood plasma into the interstitium by appropriate time-varying modification of the total blood volume. We use the experimental data of Lundvall et al.[11] for the amount of the leakage of blood plasma into interstitium.

The model was tested against published data from LBNP experiment[8] to assess its accuracy in representing the hemodynamic response to suddenly applied steps of different levels of LBNP each lasting for four minutes. Figure 4 shows that the numerical data in our model agree well with the experimental data[8] except CVP. The CVP change at -30 mmHg amounts to -6.7 mmHg in average meaning whereas the change in our model is near -4 mmHg. However, it is believed that this discrepancy of the numerical solution in CVP does not deteriorate the accuracy of the present numerical solutions, considering that there is a reported value of -4.5 mmHg in the other experiment[7] for the same level of LBNP.



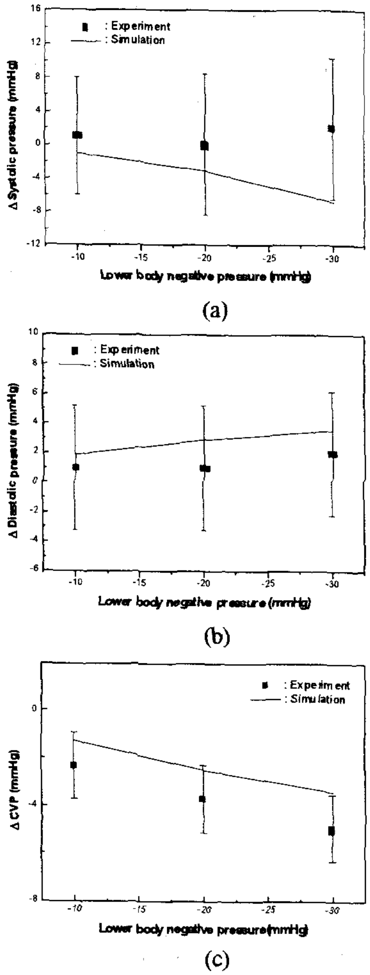
(a)

(b)

(c)

Figure 4. Hemodynamic changes during graded LBNP for the normal model. In here $\Delta(\bullet) = (\bullet)_{LBNP} - (\bullet)_{no\ LBNP}$. (a) The changes in systolic ABP (b) The changes in diastolic ABP (c) The changes in CVP.

LBNP results for the Fontan model are shown in Fig. 5. Since we utilize the same gain values for the control system, the characteristics of the hemodynamic changes for the Fontan model are similar to the ones for the normal model (see Figure 4 and Figure 5). The numerical results agree well with the experimental data of Kelley et al.[8]. The numerical results in the CVP and the systolic pressure changes shows some deviations from the experimental ones in case of relatively higher LBNP. One of the most noticeable phenomena in the hemodynamic changes of the patients after the Fontan procedure is the less decrease of CVP during LBNP. As explained in Kelley et al.[8], this is due to the increase of venous tone in case of the Fontan patients. In the numerical results we can also find the same phenomenon (Fig. 4(c) and Fig. 5(c)). The CVP decrease of the normal model at –30 mmHg is about –4.2 mmHg whereas this value is about –3.4 mmHg in case of the Fontan model. The amount of venous pooling is smaller in case of the Fontan model.



(a)

(b)

(c)

Figure 5. Hemodynamic changes during graded LBNP for the Fontan model. (a) The changes in systolic ABP (b) The changes in diastolic ABP (c) The changes in CVP.

4.3 Exposure to hemorrhage of the patients after the Fontan procedure

To show that this code can be a useful tool for investigating the hemodynamic changes of the Fontan patients under adverse conditions, we simulated the circulation in the case of exposure to hemorrhage. We assume the hemorrhage as the decrease of total blood volume in the system as in the existing computational approach[10].

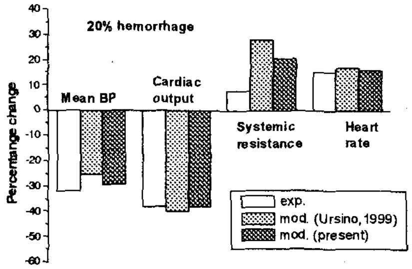


Figure 6. Percentage changes in the hemodynamic variables after 20% hemorrhage case for the normal model.

The computed results for normal subject are shown in Fig. 6 in case of 20% hemorrhage. The decrease of the total blood volume causes the arterial blood pressure and the central venous pressure to decrease, which activates the baroreceptor reflex and the cardiopulmonary reflex system. The systemic resistance modulated by the two reflex systems increases to increase blood pressure. The present numerical results are compared with the experimental one of vagotomized dogs in Fig. 6. Though there are some deviations in the systemic resistance, the other hemodynamic values agree well with the experimental one [12] and the existing numerical data[10].

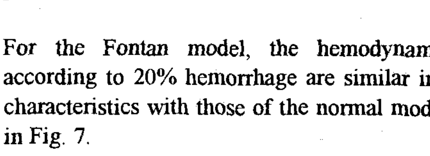


Figure 7. Comparison of the changes in hemodynamic parameters of Fontan model with normal model.

For the Fontan model, the hemodynamic changes according to 20% hemorrhage are similar in qualitative characteristics with those of the normal model as shown in Fig. 7.

The conduit resistance varies according to the fluid dynamical situation through the shunt. Here, we conduct some computation to explain the effect of the resistance. Fig. 8 shows the linear decrease in cardiac output according to the increase of the conduit resistance. Twice of the resistance increase means about 3% decrease of cardiac output, which shows the necessity of the optimal design of the shunt in fluid dynamical aspect to reduce the flow resistance.

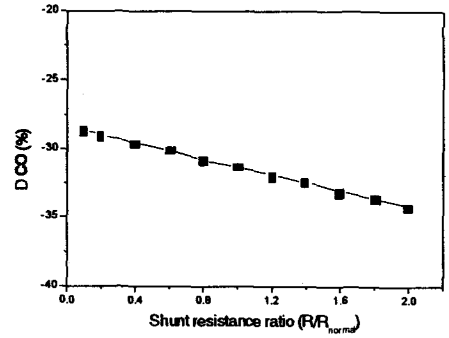


Figure 8. Cardiac output changes of a patient after the Fontan procedure according to the shunt resistance.

5. Conclusions

In this study, we presented the computational model to simulate the hemodynamic states of the patients after the Fontan procedure. The hemodynamic model of the patients after the Fontan procedure was constructed using a lumped parameter approach. To set the baseline state of the Fontan model, we assumed the increased venous tone, heart rate, systemic resistance, and the inclusion of the shunt resistance. The proposed method includes the two control mechanisms, the baroreflex receptor and the cardiopulmonary reflex model. In this study the gain values for the Fontan model are same with the normal model. LBNP simulation has been conducted for the normal and the Fontan model and their results were compared with the experimental ones. The numerical results agree well with the experimental one. The increased venous tone in case of the Fontan model cause the less decrease of CVP during LBNP compared with that of the normal model. The numerical results of 20% hemorrhage are well compared with the experimental and the existing numerical result. We have also done the parametric study according to the increase of the blood volume loss. Mean ABP and cardiac output decrease abruptly whereas heart rate and systemic resistance linearly increase as the blood volume loss increase. Numerical results of the sensitivity analysis due to the shunt resistance show the linear decrease in cardiac output according to the increase of the resistance.

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