THE EFFECT OF EECP ON THE FLOW RATE OF CORONARY ARTERIES IN HUMAN BLOOD CIRCULATION MODEL

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ABSTRACT

Background: The blood circulation in coronary arteries is different from the same task in other body arteries because on the contrary to the other arteries, the maximum blood is circulated in them during the diastole phase of heart (rest time of the heart). The changes of coronary blood circulation occur mainly due to changes in the rate of the resistance of coronary arteries. EECP is one of the new effective facilities in treatment of coronary arteries diseases and cardiac failure through increasing the flow in coronary arteries in diastole and lowering the load in systolic phase.

In the present study, firstly, the modeling of pulmonary and systemic blood circulation will be described while considering coronary arteries. Then, the obtained flow rates were from the real sample while increasing the effect of EECP will be used for studying the validity of the designed model. Through adding the effect of EECP to the model, the changes of radial artery pressure in the designed model were compared with the values obtained from the real sample and the results gained from the procedure of coronary flow changes will be studied.

In spite of increase in diastolic peak, no significant change is seen in mean arterial pressure which we deem it as the optimal results of neural control. On the other hand, coronary flow increases during EECP application.

KEY WORDS
EECP, modeling, coronary blood circulation

1. Introduction

The coronary arteries are different from other arteries because during the cardiac diastolic phase (when the heart muscle is relaxed) there is the maximum flow in them. While the other arteries receive the maximum of their required blood during cardiac systolic phase (the phase that the heart muscle is contracted). This is because while the heart muscle contracts, the coronary arteries are compressed. When the coronary arteries are narrowed or obstructed, the rate of oxygen may be insufficient for some parts of the heart.

Angina Pectoris is the most common symptom of the CAD (coronary artery diseases). For some patients, angina is the disabling factor which influences their efficiency or prevents their ordinary activities. Angina is usually controlled by medication. The medicines either increase the rate of oxygen delivery to the heart muscle through dilation of coronary arteries or reduce the rate of oxygen demand by through decreasing heart rate. They also may reduce the cardiac contractility or decrease the pressure applied to the walls of heart cavities. Unfortunately, in most patients, medication has undesirable effects in long term. If medical treatment is not effective for relief of angina and dyspnea, or the risk of cardiac death is high, coronary bypass grafting or angioplasty usually are recommended.

EECP is another alternative treatment for some of the coronary and heart failure patients. This method may control the symptoms of the disease for longer period through more and better oxygen delivering to the heart muscle. EECP is a mechanical procedure in which there is no need for any surgery and may reduce the symptoms of angina through increasing coronary blood flow in some regions of heart with low coronary flow.

EECP system pumps blood while the heart muscle is relaxed (at the onset of diastole) and reduces the aortic pressure (after load) a little before heart muscle contraction (Figure1). Thereby, EECP increases the blood flow in heart muscle and causes to reduce cardiac workload and supplies more oxygen to the heart (when the rate of oxygen required for proper function decreases). Collateral formation and angiogenesis are another suggested mechanism for increasing the coronary blood flow. For EECP treatment, the patient lays on bed while a set of pressure cuffs are wrapped around of his calf, upper thigh and lower thigh. EECP system has a pressure source which inflates and deflates the cuffs. The vascular system inside the leg muscles are contracted in turn (with intervals). The sequences of pressure application are from the calf towards upper parts. The inflation and deflation of cuffs are synchronized with cardiac cycle through ECG processing (Figure1). The simplest mechanism through which EECP causes the augmentation of collateral perfusion is the dilation of
collateral canals which have already been formed. On the other hand, this may occur directly because of the augmentation of diastolic blood pressure and flow or indirectly through releasing coronary dilating mediators such as NO\textsuperscript{7,11} (Figure 3). The main and primary stimulus for the process of changing coronary model is the increase of pressure applied to the walls which causes angiogenesis, through which EECP may cause to improve myocardial perfusion. Angiogenesis which is forming new blood capillary through producing endothelial cells from blood arteries may also be done by EECP stimulus.

The cardiologists believe that EECP is able to stimulate the growth of small arteries, so called as Collaterals in heart which is capable to increase the coronary blood flow around the obstructed arteries. Except in ischemia, the augmentation of pressure applied to arterial wall is an important stimulus for developing and innovating the collateral arteries. Therefore, it is assumed that at least a part of the useful effects of EECP is related to the development of the arteries collateral to the coronary ones because of creating pressure forces applied to the walls. The main factor in myocardial blood supply is aortic pressure which is produced by heart. The changes in aortic pressure causes direct alteration in coronary blood flow. Of course, the changes in cardiac function which occur due to augmentation or reduction in aortic pressure has a significant effect on coronary resistance. Increase in metabolic function of heart results in reducing the coronary resistance and vice versa.\textsuperscript{13}

In the present study, firstly, we have described the modeling of pulmonary and systemic blood circulation system while considering the branch of coronary arteries. The body is divided into three parts of head and neck, trunk, and legs. In previous similar researches for demonstrating changes in pulsation pressure and the blood flow in coronary arteries, the pressure source synchronized with cardiac pressure was used. While in the present study, the variable resistance has been used. Then, the values required for evaluating the validity of the designed model were obtained from the real sample while adding the effect of EECP. Ultimately, by adding the effect of EECP to the model, the changes in radial artery pressure in the designed model were compared with the values received from the real sample and the results of coronary flow changes will be studied.

2. Methods

2.1 Model of Systemic & Pulmonary Blood Circulation System

Different and numerous models have been presented for mechanics of blood circulation system which have been intense, expanded, complete or incomplete depending on the need. In the present study, one model of blood circulation system (the same as illustrated in figure8) has been used. This model has the following characteristics:

A. Its simple shape provides the possibility to be developed conveniently and the required parts to be added to it.
B. In the venous branch model, both pulmonary and systemic parts are formed of several basic sections.

C. Considering the shape of model, we are able to change the value of elements at any moment even while implementation. In this model the compliance of arteries is considered linearly.

D. A semi-sinuous wave is used for producing ventricular stiffness.

2.2 Left coronary arteries model

The right and left coronary arteries which are originated from the root of aorta at the back of the right and left cusps of aorta respectively, supply blood to the heart muscle. The flow of coronary blood is regulated by the physical, neurotic and metabolic factors. In this study we only describe the physical factors. The main effective factor in supplying blood to the heart muscle is the aortic pressure which is created by the heart. The changes in pressure cause direct changes in coronary blood flow. Certainly, the changes in cardiac function which is resulted from the increase or decrease in aortic pressure has a significant effect on coronary resistance. The increase in metabolic function of the heart muscle results in reducing coronary resistance and vice versa. In normal circumstances, the blood pressure changes relatively by baroreceptor reflex in a small range in such a way that average changes in coronary blood flow is mainly created by changes in the resistance of coronary arteries in response to the cardiac metabolic needs.

In figure 8, circular model of left coronary arteries which have been designed for adding to aortic branch is seen. The pattern of RLCA and RLCV is a semi-sinuous shape. RLCA and RLCV are dependent on changes in ventricular and auricular stiffness respectively.

2.3 Addition of EECP to the General Model of Blood Circulation System

In this phase, the following points should be considered.

A. External pumping of EECP is a source of pressure application to the lower limbs and we model it with a voltage source synchronic with the cardiac pulsation.

B. Whereas all the pressures is measured in comparison to atmospheric pressure, therefore, the rate of external voltage is always considered zero. For applying the effect of EECP, we apply it in lower limbs through a source of external pressure application in the model.

C. Considering the necessity of connecting EECP cuffs to legs, we have divided the body into three general parts including head and neck, trunk and legs so that it is possible to connect the EECP pump to the model. The final model has been designed in accordance with figure 8. In general state, the shape of diagram of EECP compressor output is shown in figure 4 which is applied in diastolic phase of heart. The rate of positive pressure is variable and depends on factors such as age and type of disease and may change up to 350mmHg.\textsuperscript{15,18}

The constant values are as shown in table 3.

3. Results

The proposed model has been simulated by using Matlab Software. The systolic and diastolic pressures are 90mmHg. and 58mmHg. respectively in the simulation. Figures 5 and 6 are about coronary flow before and after applying EECP.

Considering these two figures, it is observed that in coronary arteries the highest rate of blood flow is in diastolic phase. The maximum blood flow before applying EECP is about 104 ml/s which has reached to 155 ml/s after applying EECP.
We have studied the pressure of radial artery in different rates of EECP pressure. The numerical values of coronary blood flow will be as demonstrated in table 2. Considering tables 1 and 2, different states include changes in EECP pressure and the proportionality of applying EECP pulsation in any alternate period of cardiac pulsation.

4. Discussion & Conclusion
In the present research paper, the changes in coronary arteries and its synchronization with cardiac pulsation were equated with variable resistance which depends on cardiac pressure. This is the reason that we can study the changes in any region of the blood circulation and its effect on other regions (Figure 8). In the previous studies the dependent voltage source or electric model FET was used. With regard to Table 2, in spite of increasing diastolic peak, in a relative acceptable rate, no significant change is seen in average arterial pressure which we deem it as the optimal results of neural control. On the other hand, coronary flow increases during EECP application. As we expected, coronary flow is augmented during EECP application. Considering the fact that the cardiac output is the rate of blood output from aortic valve in one minute during cardiac systolic phase, therefore, with regard to the blood flow augmentation in coronary arteries and aortic valve, we expect that the cardiac output increases due to EECP application. On the other hand, considering the increase of venous perfusion due to counter-pulsation, the workload of heart reduces because of EECP application.

The other matter that should be stated is the fact that due to increase in aortic blood pressure and as a result in coronary arteries, the gradient of pressure along congested arterioles increases because of the same pressure, this results in better perfusion of cardiac muscle even up to 22%. Enhancement of collateral perfusion involves opening or expansion of preformed collaterals as well as formation of new collateral vessels.

Aside from ischemia, an increase in endothelial shear stress is considered a major stimulus for collateral development and recruitment, underlyingly the hypothesis that EECP may exert its beneficial effects at least in part by enhancement of coronary collateralization through development of these shear forces.

Acknowledgment
The authors of the present research paper hereby appreciate the cooperation made by the Cardiac Rehabilitation Department of Razavi Hospital of Mashhad and mrs. Azadeh Emani in collecting data from the real samples.

References
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Table 1

<table>
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<tr>
<th>Row</th>
<th>EECP pressure (mmHg)</th>
<th>Time (min)</th>
<th>Radial Artery-Real sample</th>
<th>Radial Artery-Simulated sample</th>
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<td>Systol (mmHg)</td>
<td>Diastol (mmHg)</td>
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Table 2

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<tr>
<th>Row</th>
<th>EECP pressure (mmHg)</th>
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<th>Changes(%)</th>
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Figure 7. Possible mechanism responsible for the clinical benefit associated with EECP. Acute afterload reduction decreases myocardial demand. By increasing coronary blood flow, EECP is thought to promote myocardial collateralization via opening of preexisting collaterals, arteriogenesis, and angiogenesis. Increased blood flow and shear stress may further promote collateral formation by arteriogenesis and angiogenesis. Besides a peripheral training effect, a minor placebo effect is considered to contribute to the symptomatic benefit of EECP. ET=endothelin; NO=nitric oxide.7

Figure 8. Circulation model