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On the Blood Pressure in the Cardiovascular System

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Abstract

Background: Hemodynamics is a practical and complicated theoretical problem. The aim of this paper is to analyze the characteristics of blood pressure in the cardiovascular system changing with the mechanical parameters of blood vessels and the storage of some visceral organs. **Method:** The fluid network model was used for the study. The cardiovascular system was modeled as a system consisting of 20 segments of vessels. The main controlling parameters were determined first by using dimensional analysis. Then the responses of blood pressure of each segment of vessels were analyzed by changing the controlling parameters. **Results:** The parameters of the blood vessel of brain have the least influence on the pressures of other parts. The pressures of the system of blood vessels will decrease if some blood is stored in the liver or the abdominal vein system. Vice versa. The effects of regulation of blood on the variation of blood pressure are larger than the other controlling parameters. **Conclusions:** The controlling parameters of the abdominal aorta and ascending aorta affect greatly the blood pressure of each vessel.

Keywords

Cardiovascular System, Response of Blood Pressure, Regulation of Blood Flow, Theory of Womersley

1. Introduction

The cardiovascular system of human is a network consisting of heart and is from thick to fine blood vessels. Most of the early analysis of the pulse wave and blood flow is carried out for a single blood vessel [1] [2]. However, the blood flows in the whole cardiovascular system and the influences among every segment of blood vessels cannot be neglected, so it is limited that only one blood vessel is considered in the analysis. In the latter study, researchers adopted the model of fluid network [3] [4], electro-network model [5] [6] to study the characteristics of blood flow in the whole cardiovascular system. The effects of the properties of blood vessels on blood pressure were analyzed by using the fluid network. Electro-network (or transmission line model) uses the equations of transmission line of electro-network to describe the blood flow in the cardiovascular system. In this model, the voltage, current and resistance of an electro-network are assumed as the blood pressure, blood flow volume and resistance of blood flow in a cardiovascular system. This kind of model can consider the effects of mechanical properties such as elastic modulus on the blood flow and be used in a series of studies on the blood flow of a cardiovascular system. Xiao *et al.* [7] studied the effects of the parameters of artery on the pulse wave by using electro-network model with 55 segments of transmission lines. Liu *et al.* [8] studied the effects of peripheral resistance and artery compliance on the blood pressure of the artery by using dual elastic model based on the electro-network model. Butlin *et al.* [9] studied the effects of the heart rate, left ventricular ejection time and reflected wave on the pulse wave in blood vessels with atherosclerosis by using transmission line model. Xiao *et al.* [10] [11] studied the effects of heart rate, height, radius of artery and peripheral resistance on the pulse wave, and the effects of the position and degree of arteriarctia on the blood flow and pulse tracings by using transmission line model. Zhang *et al.* [12] thought that each organ is relative with special frequency of harmonic resonance. He divided the pulse at the radial artery into harmonic waves with different frequencies and studied the corresponding harmonic frequency of a disease.

The characteristics of blood flow are close to the physiological status. Though the study on the blood flow in the cardiovascular system has been carried out for many years, the effects of factors on the blood flow are not clarified clearly.

To study the effects of physiological variation of different organs on blood flow in the cardiovascular system, the variation of the blood pressure with the parameters of peripheral blood vessels is investigated. A simplified blood vessel network is used to analyze the effects of the parameters of main organs on the blood flood such as blood pressure, blood flow volume, etc. In Section 2, the controlling equations and numerical model are introduced. The numerical results and discussions are shown in Section 3.

2. Introduction of Model

2.1. The Controlling Equations

According to Womersley's theory [13], the end effects can be neglected. The wall of blood vessel is very thin. The radial displacement is much smaller than the radius of the blood vessel. Therefore, the flow volume and average velocity can be computed by the following equations in a free elastic blood vessel:

The equation of flow volume:

$$Q=\sum_{m=0}^{\infty}\frac{\pi R^2 A_n}{\rho C_n}\left[1+\chi_n F_{10}\left(\alpha_n\right)\right]\mathrm{e}^{i\omega_n\left(t-x/C_n\right)} \tag{1}$$

The average velocity can be described by the following equation:

$$U=\sum_{m=0}^{\infty}\frac{A_n}{\rho C_n}\left[1+\chi_n F_{10}\left(\alpha_n\right)\right]\mathrm{e}^{i\omega_n\left(t-x/C_n\right)} \tag{2}$$

in which the *n*th amplitude of pressure is A_n, $F_{10}\left(\alpha_n\right)=\frac{2J_1\left(\alpha_n j^{3/2}\right)}{\alpha j^{3/2}J_0\left(\alpha_n j^{3/2}\right)}$, J_0 and J_1 are the 0th and 1th Bessel functions, $j^2=-1$, $\alpha_n=R\sqrt{\omega_n/\nu}$, ν is the dynamic coefficient of viscosity, ω_n is the nth angular frequency of pressure pulsation, R is the radius of blood vessel, C_n is the wave speed corresponding to the *n*th pressure gradient, R is the present radius. And

$$\chi=\frac{C^2\left(1-\mu^2\right)}{c_0^2\left(F_{10}-2\mu\right)}-\frac{1-2\mu}{F_{10}-2\mu},\quad c_0=\sqrt{\frac{Eh}{2\rho R_0}},\quad c=\sqrt{\frac{Eh}{2\rho\left(1-\mu^2\right)R}}$$

μ is the Poisson's ratio of blood vessel, c_0 and c are the initial and present wave speeds, h is the wall thickness of blood vessel, ρ is the blood density, R_0 is the initial radius of blood vessel. Take c_0, R_0 and ρ to normalize the above equations.

The equation of blood flow is

$$\frac{Q}{C_0R_0^2}=\sum_{m=0}^{\infty}\frac{\pi R^2 A_n}{\rho C_n C_0 R_0^2}\left[1+\chi_n F_{10}\left(\alpha_n\right)\right]\mathrm{e}^{i\omega_n\left(t-x/C_n\right)} \tag{3}$$

The equation of average velocity is

$$\frac{U}{C_0}=\sum_{m=0}^{\infty}\frac{A_n}{\rho C_0 C_n}\left[1+\chi_n F_{10}\left(\alpha_n\right)\right]\mathrm{e}^{i\omega_n\left(t-x/C_n\right)} \tag{4}$$

It can be seen that the controlling dimensionless parameters for blood flow are $\frac{\pi R^2 A_n}{\rho C_n C_0 R_0^2}$ and $\chi_n F_{10}$. The dimensionless controlling parameters for average velocity are $\frac{A_n}{\rho C_0 C_n}$ and $\chi_n F_{10}$. Generally, $\chi_n F_{10}$ can be taken as a constant, so there is only one controlling parameter for either blood flow or average velocity and their difference is that the diameter of blood vessel should be considered in the blood flow. The controlling parameters for wave shape are ω_n, C_n, respectively. In simulation, we can change the value of C_n (which is related with the modulus.) to change the controlling parameters.

2.2. Numerical Model

Take the same model of blood vessel network as that built by Xu *et al.* [14] which is an effective model for studying the dynamic of blood flow (**Figure 1**). The parameters of cardiovascular system presented by Xiao *et al.* [11] were adopted in the simulation (**Table 1**). The variation of blood flow and pulse wave was simulated by changing the parameters of the main organs. A sine wave signal simulating the blood pressure is output from the heart first and then transports

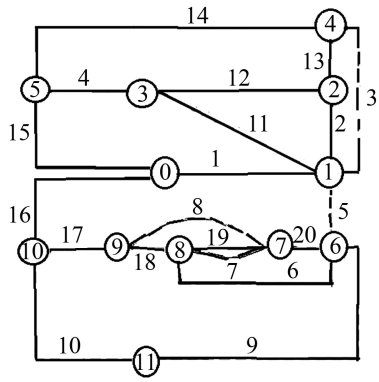

Figure 1. The model of blood vessel network. Note: Each circle denotes the node between two blood pipes. Each line denotes a branch of blood pipe. The numbers over the lines denote respectively: 1 ascending aorta, 2 truncus, 3 left common carotid, 4 capillary network of upper limb, 5 thoraco-abdominal aorta, 6 mesenteric artery and capillary network, 7 splenic artery and capillary network, 8 hepatic artery, 9 renal artery, 10 renal capillary network, 11 left subclavical artery and arteries in left arm, 12 right subclavical artery and arteries in right arm, 13 left vertebral artery, 14 capillary network in head and neck, 15 superior vena cave, 16 inferior caval vein, 17 capillary network of liver, 18 hepatic portal vein, 19 renal artery and capillary network, 20 celiac axis.

Table 1. Parameters of each segment of blood vessel.

	Radius (cm)	Length (cm)
1	0.5	13
2	0.28	20
3	0.165	30
4	0.105	11
5	0.83	20
6	0.1	11
7	0.05	1.5
8	0.055	1.44
9	0.135	22
10	0.13	22
11	0.165	31
12	0.13	11
13	0.013	11
14	0.105	11
15	0.485	60
16	0.6	60
17	0.165	10
18	0.475	8
19	0.05	1.46
20	0.22	1.46

into the whole system. The signal is shown in **Figure 2**.

The parameters used in simulation are as follows [15]:

$\frac{h}{R_0} \sim 0.1$, ρ = 1000 kg/m^3, The Poison's ratio 0.1, $f_{10}(1)$ = 0.5939, $f_{10}(2)$ = 0.3925, $f_{10}(3)$ = 0.3165, $f_{10}(4)$ = 0.2731, $f_{10}(5)$ = 0.2564

Take the corresponding wave velocity c_0 = 0.3535 m/s of the modulus e = 0.025 MPa, the density ρ = 1000 kg/m^3 and the radius R_0 = 0.05 m of the 19th segment blood vessel to normalize the problem, then the dimensionless parameters are $\bar{p} = \frac{p}{\rho c_0^2}$, $\bar{t} = \frac{tc_0}{R_0}$, $\bar{x} = \frac{x}{R_0}$.

3. The Simulation Results and Discussions

3.1. There Is No Storage/Release of Blood from Liver or Abdominal Vein

When the modulus of each segment is 2.5 MPa, the variation tendency of blood pressure at each segment is similar. But the amplitude of variation is different due to the effects of wave and the resistance (**Figure 3**). The variations of blood pressure at ascending aorta and thoracoabdominal aorta are the most obvious. The variations are several times of the other segments. Observing the variation of blood pressure after changing the dimensionless modulus $E/\left(\rho c_0^2\right)$ at different segment at a designed time (0.18 s in this paper), it can be seen that the variation of blood pressure caused by changing the parameter $E/\left(\rho c_0^2\right)$ at thoracoabdominal aorta is the most largest, while the effects of variation of the parameter $E/\left(\rho c_0^2\right)$ of liver is small. The variation of the parameter at each segment causes the largest blood pressure response of the nearest segment (**Figure 4**).

Because the radii of the ascending aorta and the thoracoabdominal aorta are large, the variation of blood pressure due to the change of dimensionless modulus is large at the same blood flow. If the modulus changes the same degree, the difference of blood pressure can be over 10 times at the segment with small changes of the parameter $\frac{\pi R^2 A_n}{\rho C_n C_0 R_0^2}$, accordingly the responses is large.

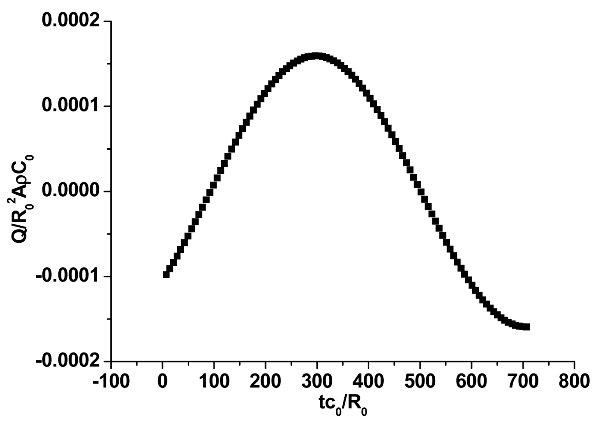

Figure 2. A sine wave signal simulating the blood pressure is output from the heart.

The variation of the parameters at the head only changes the pressure of the near segments. The following figure is the result at time of 0.18 s. The changes in the parameters of the gastric artery and capillary network have great influences on the blood pressure of other segments (Figure 5 and Figure 6). The reason is that the radius of this segment is small. The blood flows through a short distance before returning to the heart.

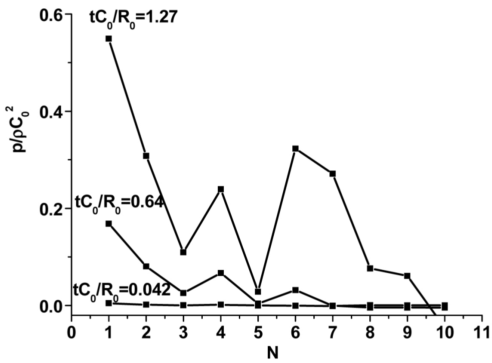

Figure 3. The changes in blood pressure with time (the moduli of all segments are 2.5 MPa. N denotes the number of the segment).

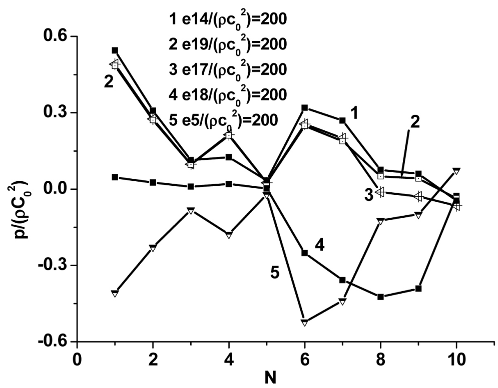

Figure 4. The changes in blood pressure with the changes of modulus of some segment. In each condition, the dimensionless modulus of one segment (5, 14, 17, 18, 19) change to 200. The moduli of other segments are 2000.

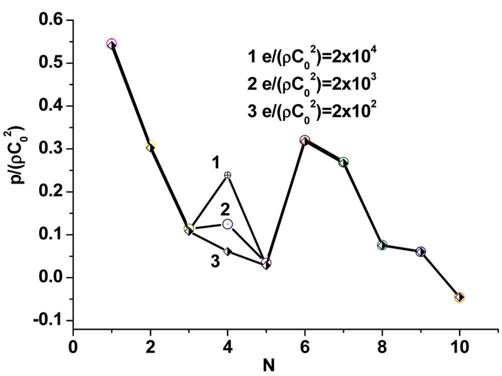

Figure 5. The blood pressure at the modulus of segment 14 equals 2.5 MPa, 0.25 MPa, 0.025 MPa, respectively.

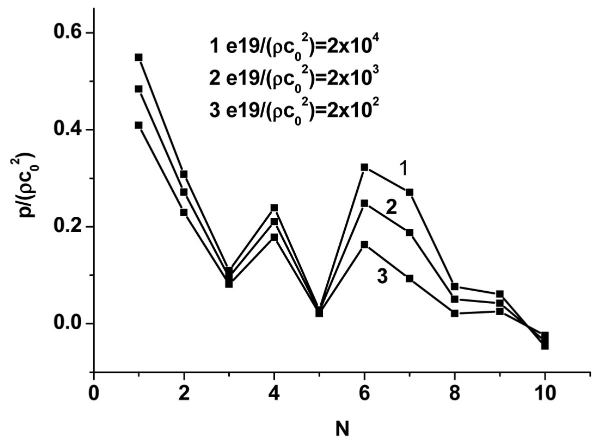

Figure 6. The changes in blood pressure with the modulus of segment 19.

Obvious changes can be caused by the variation of the parameters of the hepatic portal vein, especially the blood pressures at the entrance of the hepatic portal vein and the output port of the heart (**Figure 7** and **Figure 8**). Because the liver is connected with the main organs in the abdomen and its radius and length of the blood vessel are both large.

3.2. There Is Storage/Release of Blood from Liver or Abdominal Vein

Generally, the liver and the blood network in the abdomen have the function of regulating the total blood flow in the vessel system, *i.e.*, storing or releasing blood into the blood vessels according to the status of the body. Numerical results show that the regulation of the liver to the blood flow affects the blood pressure and distribution of every segment. If the blood stored in the liver is released into the network of blood vessels, the pressure in the network will increase. The variation increases with the rise of the modulus of the liver (**Figure 9**). The influences on the heart and the segments connected with the liver are large. This may be the reason that the blood pressure will increase when one is angry when the liver will shrink.

Similarly, when the blood is released from the vessel network in the abdomen, the pressure increases in the whole blood vessel network. The effects of modulus are smaller than the blood release (see 3, 4 conditions in **Figure 10**). However, the relative changes are smaller than that of the variation of the blood released from the liver.

A little change in the blood flow at segment 18 (portal vein) can cause obvious variations in the blood pressure in the cardiovascular system. The variation in the parameters of the whole cardiovascular system is obviously larger than that in one segment. For example, when the modulus of the whole cardiovascular system increases 10 times, the maximum pressure increases 12 times, while the maximum pressure increases 5 times when the modulus of the liver's capillary network increases 10 times (**Figure 11** and **Figure 12**).

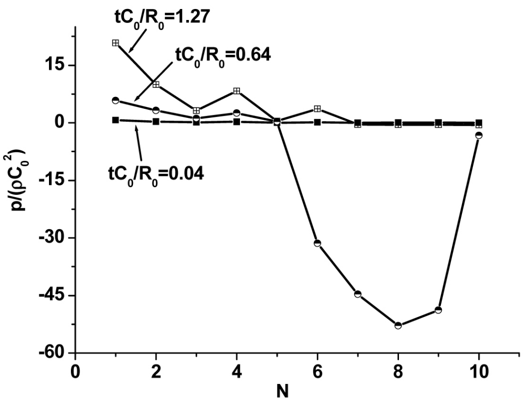

Figure 7. The blood pressure with time at the modulus of segment 18 equals 0.25 MPa.

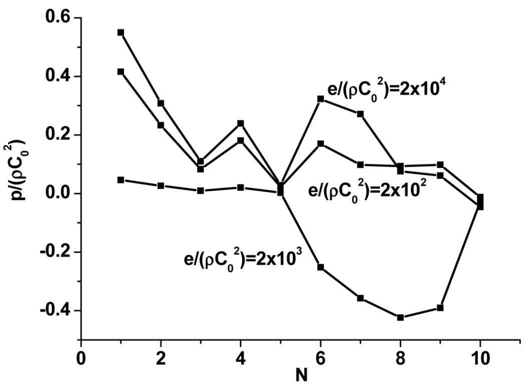

Figure 8. The changes of blood pressure with modulus of segment 18.

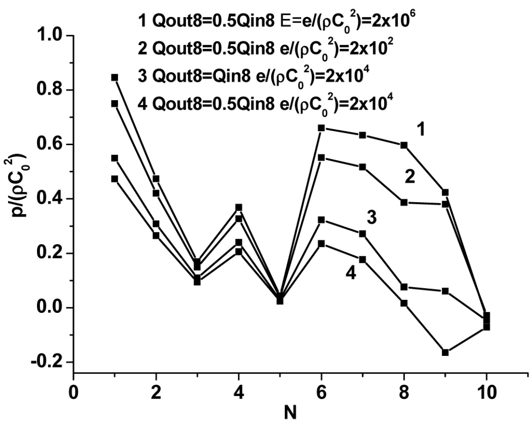

Figure 9. Changes in blood pressure with flux and modulus of segment 19 (Segment 18, 0 indicates no modulus equals 2.5 MPa).

4. Discussion

The responses of the cardiovascular system are controlled by the main dimensionless mechanical parameters of the vessels. The elastic modulus of the vessel determines the deformation and inversely affects the flow resistance. So the blood pressure changes more obviously with the decrease of the elastic modulus. Surely, the effects of the elastic modulus are limited by the scale of the vessel

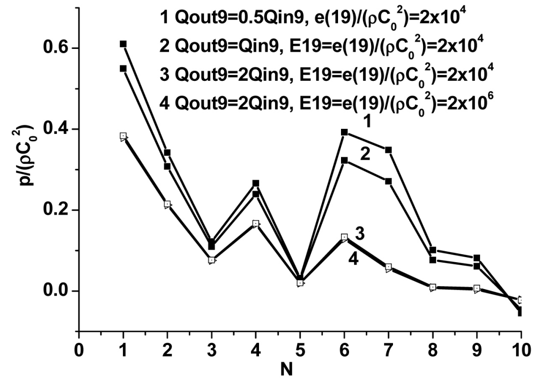

Figure 10. Changes in blood pressure with storage/release and modulus of segment 19, 0 indicates no storage/release, storage/release.

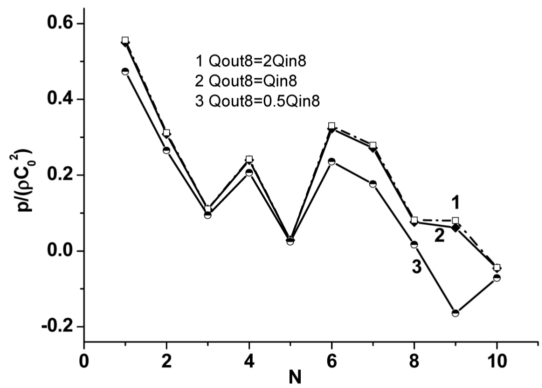

Figure 11. Changes in blood pressure with storage/release of blood (Segment 18 equals 25, 2.5 MPa and 0.25 MPa the change of storage volume).

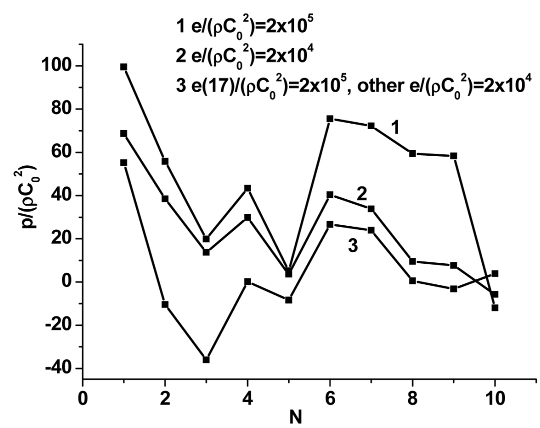

Figure 12. Changes in blood pressure with storage/release of blood (Only the modulus of segment 17 equals 25 MPa, the others equal 2.5 MPa).

(length and diameter). The smaller the length and diameter, the effect of this section of vessel is smaller because its blood volume is smaller relative to other sections. The responses increase with the rising pressure amplitude A_n because the amplitude means the strength of the applied pressure. Inversely, the flow resistance has the function to decrease flow velocity and pressure because it indicates energy consumption. The storage/release of blood from some organs means the decrease/increase of blood volume flowing in the whole vessel system. In other words, the storage/release of blood means the decrease/increase of blood pressure. From the numerical results, we can see that the changes in the property of any section will affect the other section of the vessel system. However, the method used in this paper cannot perfectly reflects the effects of joint between any two sections of the vessel system, e.g., reflection of pressure wave.

5. Conclusion

The controlling parameters of the abdominal aorta and ascending aorta affect greatly the blood pressure of each vessel. Changes in the mechanical parameters of any vessel will bring changes to the whole system. The pressures on the system of blood vessels will decrease if some blood is stored in the liver or the abdominal vein system. Vice versa, the effects of regulation of blood on the variation of blood pressure are larger than the other controlling parameters.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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