A method to personalize the lumped parameter model of coronary artery

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Abstract

Lumped parameter model is a 0 dimensional (0D) model which uses circuit to simulate the cardiovascular circulatory system based on the similarity of circuit and blood vessel. Due to the invasive measurement of physiological indicators in the coronary heart disease surgery, lumped parameter model was used to compute the pressure and flow rate in coronary artery before the surgery. It's a conventional and effective simulation method for appropriate surgical planning. However, due to the specificity of blood vessel structure, thickness and blood viscosity and other physiological parameters of each patient, differences of hemodynamic simulation results ought to exist. If the same parameters of every circuit element in the model were used to simulate cardiovascular system, what is difficult to convincing is that results couldn't reflect the actual situation of each one. In this study, a method which can personalize the lumped parameter model of cardiovascular system based on the non-invasive physiological parameters has been developed. The parameters of cardiovascular system based on the non-invasive physiological parameters physiological parameters. The heart module was determined by systolic blood pressure (SBP), diastolic blood pressure (DBP) and heart rate; the systemic circulation module was determined by cardiac output and Cardio-ankle vascular index (CAVI), while the CAVI was determined by age, height, SBP and DBP; the coronary module, which is most important, was determined by the target waveforms of coronary flow rate predicted from cardiac output. Based on the physiological parameters of a patient provided by Beijing Anzhen Hospital, genetic algorithm was used to optimize the parameters of each module. The considerable results after optimization proved that this method can be applied to each patient. According to the actual physiological parameters of patient, the corresponding changes in the structure and the optimization of parameters of model were necessary procedures to determine the patient-specific treatment.

Keywords: personalize, coronary artery, lumped parameter model, physiological parameters

Introduction

For patients with coronary heart disease, the internal hemodynamic parameters of coronary artery such as coronary flow, pressure, wall shear stress (WSS) and oscillatory shear index (OSI) is not easy to be measured before and during the surgery due to technical and ethical limitations. But these indicators are of great reference significance for preoperative surgical planning and decision-making. Although hemodynamics in the human body can be simulated by animal experiments, the details of the blood flow still will miss due to the limitations of the experimental conditions [1, 2]. While with the development of computer science, computational numerical simulation of fluid flow has been applied to many studies [3]. Therefore, establishing the coronary artery model for patients with coronary heart disease by the technology of computational numerical modeling, and executing detailed simulation focus on the intracoronary hemodynamics of coronary artery are very effective and necessary means.

Lumped parameter model is a common 0D numerical model, which uses circuit elements to simulate the cardiovascular circulation system. The physiological parameters and characteristics of human body can be reflected through it [4]. In the model, the resistance is used to simulate the viscous resistance of blood flow and the resistance of vessel wall; the capacitance is used to simulate the compliance of the vessel wall; the inductance is used to simulate the flow inertia of blood; the diode is used to simulate the valve, which makes the unidirectional flow in some particular structure. The model is based on the Kirchhoff's law, and

the differential-algebraic equations were used to describe the circuit [5]. Frank [6] compared the computation results of lumped parameter model with the blood flow characteristics of blood circulation system, and many similarities were found to prove the effectiveness of the model. Manor [7] has an initially discussion on the lumped parameter model of coronary artery, which provided a theoretical basis for the construction of the model. In the study of treatment direction for coronary artery disease, Taylor [8] used a multi-scale method coupled by lumped parameter model and 3D model. On the basis of this method, Kim [9] predicted the flow rate and pressure inside the coronary arteries for personalized patient with coronary heart disease, but the parameters of lumped parameter model used were not personalized. Burattini and Van Huis [10, 11], respectively, estimated the proximal and distal resistance and compliance of coronary artery through the animal experiment, the parameters used provided a reference value in this study. Taylor and Draney had more deep research in the application of the description of blood flow by lumped parameter model [12].

Based on the CTA image of patients with coronary heart disease, the patient-specific 3D model of coronary artery can be obtained by the technology of three-dimensional reconstruction. Because of the actual characteristics of intracoronary blood flow, and in consideration of the interaction between the heart and the coronary artery, the lumped parameter model of heart should be coupled at the inlet of 3D model; and because of the resistant and compliance exist in the coronary artery, microcirculation and veins, the lumped parameter vascular bed model should be coupled at the outlet of the coronary artery of 3D model [9]. Zhao [13] developed the coupling algorithm. By this algorithm, the 3D model and the lumped parameter model were coupled to obtain the patient's geometric multi-scale model, which was used to simulate the circulation system focus on the coronary artery. The geometric multi-scale model is shown in Fig. 1.



Figure 1 The geometric multi-scale model of coronary artery

In the geometric multi-scale model, the lumped parameter model is used to provide boundary condition of inlet and outlet for the coronary artery of 3D model. For patients with coronary artery stenosis, a similar geometric multi-scale model can be established, and the simulation of different bypass surgery based on this model can be executed. After the hemodynamic simulation calculations, the flow rate, pressure, WSS and OSI inside coronary artery can be observed. Optimal values of these indicators under different bypass surgery, resulting in the best surgical approach for each patient. However, it is precisely because of the specificity in structure, vascular thickness and vascular length of each patient, the parameters of lumped parameter model coupled to the inlet and outlet of coronary artery should be adjusted based on the physiological parameters appropriately, thus to ensure that the simulation results are personalized.

In this study, according to a patient's physiological data provided by Beijing Anzhen Hospital, including age, height, blood pressure, cardiac output and coronary artery CTA images, based on the personalized CTA images and the technology of 3D reconstruction, personalized geometric multi-scale model of coronary artery was built after the coupling by 3D model and lumped parameter model. The parameters of lumped parameter model were adjusted to promise the specificity of patient according to the measured non-invasive physiological parameters. We adjusted the heart module coupled to the inlet of coronary artery according to the patient's aortic pressure (including systolic and diastolic blood pressure), adjusted the systemic module coupled to the outlet of circulatory artery based on its cardiac output, aortic pressure, age and height, and finally genetic algorithm was used to optimize the parameters of coronary module coupled to the outlet of coronary artery. Once the simulation waveforms were similar to the target waveforms, the personalized parameters suitable for the patient would be got.

Methods

Building the personalized geometric multi-scale model

According to the coronary artery CTA images of 512 * 512 pixels of 200 patients provided by Anzhen Hospital, 3D model of coronary artery was reconstructed by three-dimensional reconstruction software such as Mimics. According to the results of 3D reconstruction, the lumped parameter model representing heart was coupled to the inlet of 3D model, the lumped parameter model representing systemic circulation was coupled to the outlet of systemic circulation artery, and the lumped parameter coronary vascular bed model was coupled at the outlet of coronary artery, then the personalized geometric multi-scale model of patient was got, as shown in Fig. 2.



Figure 2 The personalized geometric multi-scale model of patient

In the lumped parameter model of heart module, the function to simulate the ventricular systole was applied to the variable capacitance C(t). Suga and Sagawa [14] established the ventricular pressure-volume relationship by animal experiments, which can be expressed by the time-varying function E(t) as Eq. (1):

$$E(t) = \frac{P_{SV}(t)}{V_{SV}(t) - V_0}$$
(1)

Where E(t) is time-varying function (mmHg/ml), $P_{sv}(t)$ is time function of ventricular pressure

(mmHg), $V_{sv}(t)$ is time function of ventricular volume (ml), V_0 is ventricular reference volume (ml), and that is theoretical volume relative to the "zero ventricular pressure". Based on Eq. (1), Boston [15] sorted out the function which can express ventricular systole by mathematical fitting:

$$E(t) = (E_{\max} - E_{\min}) \cdot E_n(t_n) + E_{\min}$$
⁽²⁾

Where the E_{max} is related to ventricular pressure-volume relation during end-systole, while the E_{min} is related to ventricular pressure-volume relation during end-diastolic, and the $E_n(t_n)$ is double hill function [16]:

$$E_{n}(t_{n}) = 1.55 \left[\frac{\left(\frac{t_{n}}{0.7}\right)^{1.9}}{1 + \left(\frac{t_{n}}{0.7}\right)^{1.9}} \right] \left[\frac{1}{1 + \left(\frac{t_{n}}{1.17}\right)^{21.9}} \right]$$
(3)

Where t_n is t/T_{max} , while the T_{max} can be calculated by the cardiac cycle t_c :

$$T_{max} = 0.2 + 0.15t_c \tag{4}$$

 $E_n(t_n)$ was called the normalization function of ventricular elasticity, which was applied to the variable capacitance C(t) in the Fig. 1. Then a pressure waveform that simulates ventricular systole generated on C(t) as shown in Fig. 3. After the computation by lumped parameter model, the time-varying pressure was converted to a waveform of flow rate at AOA in Fig. 2 to provide boundary condition of flow rate for the inlet of 3D model.



Figure 3 The pressure waveform of left ventricular

While, in the lumped parameter model of coronary module, R represents the resistance of coronary artery, R_m represents the resistance of coronary microcirculation, R_v represents the resistance of coronary artery, C_m represents the compliance of coronary artery, C_m represents the compliance of coronary microcirculation [9]. Different values of resistance and capacitance produce different waveforms of coronary flow rate at the outlet of coronary artery. Therefore, for personalized patients, the value of each parameter should be personalized. Similarly, in the lumped parameter model coupled to the outlet of systemic circulation arteries, R and C represent the resistance and compliance of the systemic circulation vessels, respectively. There is an impedance at each outlet of 3D model, which provides pressure boundary conditions for the

outlet of it. The next step is personalizing the parameters of the lumped parameter model at the inlet and outlet of 3D model.

The personalization of parameters in lumped parameter model of each module

Due to the calculation of geometric multi-scale model is very time-consuming, it is impractical to try many different parameters to execute the calculation. Therefore, the pure lumped parameter model was used to replace the multi-scale model. In this case, the trunks of coronary artery in the 3D model were replaced with the classical three-element windkessel model [17], and the lumped parameter vascular bed model was connected to the end of each branch, just as in the multi-scale model. Based on the personalized coronary structure of the patient, the final structure of pure lumped parameter model is shown in Fig. 4.



Figure 4 Lumped parameter model of blood circulation system, A represents the heart, B represents the systemic circulation artery, C represents right coronary, D represents left anterior descending artery, and E represents left circumflex branch

Based on the final structure, the parameters of blood circulation system could be personalized. The system could be divided into three modules: the heart module, the systemic circulation module, and the coronary module. The personalization of each module was based on different physiological parameters. Firstly, the parameters of heart module were personalized. The function of this module is providing the aortic pressure (including systolic and diastolic blood pressure), cardiac output and cardiac cycle (waveform cycle) to the circulatory system. It can be obtained from Eq. (2) that different values of E_{max} and E_{min} will affect the output of ventricular systole function, resulting in different aortic pressure and cardiac output waveforms. Therefore, the SBP, DBP and cardiac output of patient should be considered when the E_{max} and E_{min} were adjusted. While, the aortic pressure and cardiac output were not determined by E_{max} and E_{min} entirely, because there exists impedance of systemic circulation and coronary at the outlet of heart, and the magnitude of impedance also affects cardiac output and aortic pressure. Secondly, the personalization of parameters in systemic circulation module was executed. Because of the effects on flow rate and pressure of coronary artery by different resistance and compliance of systemic circulation, the parameters of this module were personalized. The resistance of this module, such as Rdoap, Rdoad in Fig. 4, were determined by the cardiac output of patient. The specific adjustment method of E_{max} , E_{min} and resistance of this module will be described later. The capacitance values of systemic circulation module, such as Cdoa and C, could be adjusted according to the heart-ankle index (CAVI) and the aortic pressure. CAVI is an index which can evaluate the compliance of aorta, thoracic aorta, abdominal aorta, femoral artery to the ankle artery. The relationship between CAVI and the pulse wave velocity is shown in Eq. (5) [18].

$$CAVI = \frac{2\rho}{\Delta P} ln(\frac{P_s}{P_d}) PWV^2$$
(5)

Where ρ is blood density, ΔP is the differential pressure between systolic and diastolic blood pressure, P_s is systolic blood pressure, P_d is diastolic blood pressure, PWV is pulse wave velocity, and according to the famous Moens-Korteweg Eq. (6) [19]:

$$PWV = \sqrt{\frac{Eh}{2\rho R}} \tag{6}$$

Where E is the elastic modulus of blood vessel, h is the average arterial thickness, and R is the average radius of artery. Combining with Eq. (5) and Eq. (6), the relationship of elastic modulus and CAVI could be summarized as Eq. (7).

$$E = \frac{CAVI(P_s - P_d)R}{ln\left(\frac{P_s}{P_d}\right)h}$$
(7)

While in the establishment of lumped parameter model, the vascular compliance equation is:

$$C = \frac{3\pi R^3 L}{2Eh} \tag{8}$$

Where C is the compliance of blood vessels, L is the total length of blood vessels, and h is the average thickness of blood vessels. Combining with Eq. (7), the equation of CAVI about the compliance of lumped parameter model would be got.

$$C = \frac{3\pi r^2 Lln(\frac{P_s}{Pd})h}{2CAVI(Ps-Pd)}$$
(9)

Where L is the distance from heart to ankle, about the height of human body multiplied by 0.8, h is average arterial thickness from heart to ankle, usually is 0.64mm, r is the average arterial radius, Usually is 2.1mm. By the above equation, the personalized average arterial compliance could be estimated through the patient-specific SBP, DBP, height and CAVI. But the measurement of CAVI is more cumbersome, so this study carried out a research about the relationship between CAVI and the non-invasive physiological parameters. Through the physical examination data of 195 teachers provided by Beijing University of Technology Hospital, such as height, body weight, Body Mass Index (BMI), SBP, DBP, CAVI, ankle brachial index (ABI), Heart rate and blood viscosity, by the method of multiple linear regression analysis, conclusion could be obtained. The critical threshold of CAVI is recognized as 9.0. In the analysis, IBM SPSS Statistics 19 was used to gather statistics, t test was used for the comparison between groups, and the x^2 test was used for technical data.

Finally, the personalization of lumped parameter coronary vascular bed model coupled to the outlet of 3D model was executed. In this study, the genetic algorithm [20] was used to optimize the parameters of this module according to the patient-specific waveforms of coronary flow rate. Genetic algorithm is a computational model of the evolutionary process of natural selection and genetic mechanism of Darwinian biological evolution. It is an optimization method to search the optimal solution by simulating the natural evolutionary process. The first step of genetic algorithm was establishing the target of optimization. The waveforms of patient-specific aortic pressure, cardiac output and coronary flow rate of each branch were treated as target waveforms. The SBP, DBP and cardiac output of patient could be measured, and the waveforms of aortic pressure and cardiac output could be fitted based on the measured data. While, the flow rate of coronary blood is difficult to be measured in clinical, but it could be predicted by cardiac output. According to the study of patient-specific flow rate of coronary by Kim [9], under the rest state, the total flow rate of coronary is 4% of the cardiac output, the average flow rate of left anterior descending branch is 1.3 ml/s, and the average flow rate of left circumflex branch is 1.5 ml/s, and the average flow rate of right coronary is 0.6 ml/s. Of course, the above data will not be applicable to each patient, but could be used as a general reference range, because of the little difference of coronary flow rate between each patient. In this study, the personalized coronary flow rate of patient was predicted according to the theory of Hagen -Poiseuille hemodynamics. The WSS is similar in the vascular of same level, and by the Hagen - Poiseuille shear stress equation:

$$WSS = \frac{4\mu}{\pi d^3} Q \tag{10}$$

Where μ is the blood viscosity, d is the diameter of blood vessel, and Q is the flow rate of blood vessel. Based on Eq. (10), in the ideal model, the WSS in the vascular of same level is approximately equal, so the flow ratio is third power of the diameter ratio at the bifurcation of vessel. Based on the above theory, the flow rate of left and right coronary was predicted in this study. The diameters of each branch of coronary arteries were measured in the SolidWorks based on the result of 3D reconstruction of coronary CTA images. And according to Eq. (10),

the flow rate of each branch was allocated based on the diameters measured and the total flow rate of coronary. For example, for the vessel in Fig. 5, the principle of blood flow allocation is shown in Eq. (11).

$$\frac{Q_1}{Q_2} = \left(\frac{D_1}{D_2}\right)^3$$
(11)

Figure 5 The bifurcation of vessel

Where Q is the flow rate of vessel and D is the diameter of vessel. After obtaining the average flow rate of each branch, the waveform of each flow can be fitted according to the above data. Due to the distal branch of left anterior descending and left circumflex are mainly attached to the left ventricle, they will be squeezed by the ventricular systole, so the blood of left coronary is mainly supplied in the systole; and due to the distal branch of right coronary is mainly attached to the right ventricle, in which the systolic pressure is much smaller compared with the left ventricle, so the blood of right coronary is mainly supplied in the systole [9]. In addition, the peak value of left coronary flow rate in the systole should be 40-50% of it in the diastole flow [21]. The waveforms of left anterior descending branch, left circumflex branch, and right coronary flow rate were shown in Fig. 6.



Figure 6 The waveforms of LAD, LCX, and right coronary flow rate Through the above method, the personalized waveforms of aortic pressure, cardiac output and

flow rate of each branch could be obtained and treated as the target waveforms. In the process of optimization, the genetic algorithm invoked the simulation function of cardiovascular system, and calculated the root mean square error of simulation waveforms and standard waveforms to be the target function, as shown in Eq. (12). And these errors are the fitness values of the various groups in the process of heredity, but also the ultimate goal of optimization.

$$f = \sqrt{\frac{1}{K} \sum_{n=1}^{K} |y_n - y'_n|^2}$$
(12)

Where y_n is the data of target waveforms, y'_n is the data of simulation waveforms. After determining the optimization goals, the search range of parameters value in the lumped parameter model needs to be given, including E_{max} , E_{min} , Rdoap, Rdoad, and the other parameters in cardiovascular system. We have initial value of each parameter based on the experience of adjusting them manually. Of course, these values are not applicable to each patient, but we can set the search range according to them. In the algorithm, all parameters of the simulation circuit were regarded as each individual of population, and each population generation was generated from the search range. In this study, the simulation waveforms and the target waveforms were compared innovatively, and the program would adjust the search range automatically based on comparison results, which made the optimization better and faster. Finally, in the main part of the algorithm, the parameters of lumped parameter model were optimized based on the root mean square error between the standard waveforms and the simulation waveforms. If the error was less than 5%, the obtained parameters could be considered as patient's personalized parameters of lumped parameter model. The flow chart of the optimization algorithm is shown in Fig.7.



Figure 7 The flow chart of optimization algorithm

Simulation details

In this study, the genetic algorithm was used to optimize the parameters of circulatory system. Each parameter variable was the chromosome of each individual, and each chromosome was binary coded. For each chromosome, the range of values was given according to the different parameter types. The maximum range was the coronary microcirculation resistance R_m , the range was [10, 300], and the smallest range was the coronary artery capacitance C, the range was [0, 1]. Because of the values of capacitance were small, the required accuracy was 4 decimal places, which would require the range of chromosome values x_i was $(b_i - a_i) \times 10^5$ at least. According to Eq. (13), the coding string length m_i , and the gene length would be determined:

$$2^{m_i - 1} < (b_i - a_i) \times 10^5 < 2^{m_i} \tag{13}$$

From the above equation, it could be obtained that m_i is 25, so the length of chromosome gene was 25. In this study, the number of coronary branches was 14, and five parameters required to be optimized for each branch. Including E_{max} , E_{min} and Rdoap et al., the total number of parameters required to be optimized was 102, so the number of chromosomes was 102. The genetic crossover rate was 0.7, the mutation rate was 0.02, and the genetic generations were 400. Through programming, CPUs were fully invoked by multi-threaded technology for simulation. The size of population in the algorithm was 64, in order to adapt to the core number of CPU, and achieve multi-threaded computation. As a result, computation time reduced and optimization efficiency was improved.

Results and conclusions

Correlation between CAVI and Physiological Parameters

There were 195 samples, and the comparison between normal group and risk group about the correlation between CAVI and physiological parameters is shown in Table 1.

Physiological	CAVI≤9.0(n=143)		CAVI>9.0(n=52)		t/x^2	Р
parameters	Average	Standard deviation	Average	Standard deviation		
Age(year)	52.04	10.44	67.12	9.05	-9.22	0.001
Height(cm)	164.34	7.06	165.77	6.63	-1.273	0.212
Weight(kg)	64.88	10.51	67.21	10.04	-1.38	0.178
$BMI(kg/m^2)$	23.89	2.90	24.37	3.14	-0.98	0.321
SBP(mmHg)	125.72	12.72	143.33	15.26	-8.09	0.003
DBP(mmHg)	78.61	8.58	85.08	8.68	-4.64	0.003
Heart	69.15	10.65	69.21	9.77	-0.04	0.976
rate(times)						
ABI	1.08	0.09	1.11	0.08	-2.78	0.013
Blood viscosity	5.39	0.42	5.24	0.34	2.31	0.025
(mPa·s)						

Table 1 The comparison between normal group and risk group

Pearson correlation analysis of CAVI and physiological parameters showed that CAVI was linearly related to age, systolic and diastolic blood pressure. The correlation coefficient between CAVI and age is r = 0.760, P < 0.01; correlation coefficient between CAVI and SBP is r = 0.540, P < 0.001; correlation coefficient between CAVI and DBP is r = 0.365, P < 0.01. The results of their multiple linear regression analysis are shown in Table 2 and Eq. (14).

Physiological	Regression	Standard	Standardized regression	Т	Р	_
parameters	coefficients	error	coefficient			
Age(year)	0.071	0.639	0.599	10.336	0.001	_
SBP(mmHg)	0.023	0.008	0.253	3.031	0.003	_
DBP(mmHg)	-0.005	0.012	-0.034	-0.645	0.003	_
CAVI = 0.071 * Age + 0.023 * SBP - 0.005 * DBP + 1.393248						

Table 2 The results of multiple linear regression analysis of influencing factors of CAVI

By the above equation, the value of CAVI can be estimated by age, systolic and diastolic blood pressure, and according to Eq. (9), the personalized average arterial compliance of patient can be estimated by CAVI and height, which could be used to determine the capacitance of systemic circulation module.

Optimization results of parameters

In this study, coronary CTA images and physiological parameters of patient with coronary heart disease were collected, such as aortic pressure (systolic and diastolic blood pressure), cardiac output, height, age, heart rate and so on. The patient was 50 years old, the height was 1.62 meters, SBP was 140 mmHg, DBP was 80 mmHg, cardiac output was 5.5 L/min, heart rate was 85 beats/min. According to the prediction method of coronary flow described above, the total flow rate of coronary was 4% of cardiac output, and that was 3.667 ml/s. The dominant type of coronary artery was left dominant type, and the flow rate of left and right coronary was 14:3. The flow rate of left coronary was 3.020 ml/s and the flow rate of LAD was 1.786 ml/s, and the flow rate of LCX was 1.881ml/s. The diameter measured by Solidworks and flow rate predicted following the Hagen - Poiseuille law of each branch are shown in Table 3.

	Branch number	Diameter(mm)	Flow rate(ml/s)
	а	1.730	0.684
LAD	b	2.196	0.623
	с	2.007	0.479
LCX	d	1.324	0.309
	e	1.302	0.210
	f	1.209	0.168
	g	1.064	0.148
	h	2.183	0.536

Table 3 The diameter and predicted flow rate of each branch of coronary artery

	i	1.298	0.074
	j	1.077	0.055
	k	2.058	0.381
Right coronary	1	1.773	0.136
	m	1.732	0.126
	n	2.282	0.385

Based on the flow rate and standard waveform of each branch, the personalized waveforms of coronary flow rate could be fitted. The waveforms of aortic pressure, cardiac output and each coronary flow were treated as target waveforms. The results of optimization by genetic algorithm is shown in Fig. 8.



Figure 8 Waveforms of optimization results

As it was shown that the target waveforms were similar to the optimized simulation waveform, and the optimization effect was good, which proves the practicability of this method. The values of parameters of lumped parameter model are shown in Table 4.

	Table 4 The parameter values of LPM
Units:	Resistance (mmHg s/ml), Inductance (mmHg s ² /ml), Capacitance (ml/mmHg)

Heart module		Rla 0.0037	<i>Rlv</i> 0.0010	<i>Lla</i> 0.0028	<i>L0</i> 0.0045	<i>C0</i> 0.9500
		Rp	Rd	С		
C	DOA	0.2830	1.6046	0.5241		
circulation module	RCA	3.3875	23.3258	0.0328		
	RSA	1.5228	10.8912	0.0330		
	LCA	2.0988	2.8714	0.0361		
	LSA	2.4877	16.1566	0.0287		
Coronary module		R	R_m	R_v	С	Cim
	a	74.5897	118.1439	59.7817	0.00067	0.0045
	b	66.0806	121.7862	63.1510	0.00066	0.0066

с	150.0712	282.3035	85.3090	0.00077	0.0069
d	108.8882	150.1549	79.29208	0.00049	0.0044
e	114.9609	295.7461	118.7321	0.00074	0.0071
f	132.6122	234.5194	110.2857	0.00059	0.0049
g	134.1361	170.0063	104.3336	0.00051	0.0081
h	117.0208	141.4654	122.2045	0.00058	0.0072
i	77.79236	156.5535	125.8896	0.00038	0.0049
j	108.8599	103.9168	120.3035	0.00030	0.0061
k	133.5083	179.2889	139.7658	0.00059	0.0066
l	59.1354	238.6547	80.0720	0.00051	0.0031
т	55.3238	169.4415	132.2594	0.00025	0.0023
n	70.4592	104.8977	118.2161	0.00023	0.0035

While the E_{max} was 1.0, E_{min} was 0.0305, and the value of *C* was 0.0031. In Fig. 4, the parameters such as *R1*, *C1* and *L1*, which were used to simulate the trunk of coronary artery, had little effect on the flow rate of each branch. So the values of these parameters were small. In order to save the calculation time, it's unnecessary to optimize them. In this study, *R* was 3.5, *C* was 0.00005, *L* was 0.01.

summary

In this study, by the CTA images of coronary artery of a patient provided by Beijing Anzhen Hospital, the personalized lumped parameter model structure of coronary artery was established; by SBP, DBP and age of patient, the personalized CAVI value was estimated, and the average arterial compliance was estimated further; by cardiac output, the personalized flow rate waveforms of each branch of coronary artery were predicted, and the genetic algorithm was used to optimize the parameters of personalized lumped parameter model of coronary artery, which was applied to the patient. All the programming was finished by C# based on the visual studio 2013 development environment. When a simulation of the personalized cardiovascular system was executed, these parameters were significant basis, which will be great significance to clinical preoperative surgical planning.

Limitation and expectation

In this study, we propose a series of methods to determine the parameters of lumped parameter model of cardiovascular system. The genetic algorithm was used to optimize the parameters to achieve the simulation waveforms is similar to the target waveforms. However, since the target waveform of coronary flow is not a real clinical measure, the parameter values determined in the present study can be used to calculate the fractional flow reserve (FFR) of patients with coronary artery stenosis in subsequent studies. Comparing with the clinical FFR, so as to verify and improve the method. In addition, although the technology of multi-threading was used to optimize the parameters of lumped parameter model to improve the efficiency, but the reconstruction process of 3D model for coronary is time-consuming, preoperative surgical planning still need some time to prepare, there are some limitations. In the future work, we are supposed to find a quick method to understand the coronary structure and predict the flow rate of each branch, which will achieve the rapid personalization of lumped parameter model, and provide effective reference value for the rapid clinical preoperative surgical planning of patients.

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