Pulse Wave K Value Averaging Computation and Pathological Diagnosis

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***Abstract*—Many cardiovascular diseases will lead to changes in pulse wave. Pulse wave's transmission will play a significant role in promoting the clinical detection and diagnosis, one kind pulse wave computational method based on averaging method is proposed, and computing cardiovascular function parameter K according to the waveform area, the K value is associated with pathological analysis and diagnosis. A large number of clinical simulation and experiments proved that the relationship between the form factor K value and the human cardiovascular health, the pulse wave of the cerebral infarction matches with the actual clinical detection, it can provide theoretical support for the non-invasive detection and parametric analysis of the cardiovascular function.**

***Index Terms*—pulse wave, averaging computation, cerebral circulation, pathological diagnosis**

I. INTRODUCTION

As the cycle of contraction and relaxation of the heart, blood pressure, blood flow velocity and blood flow's pulsation and vessel wall changes' expansion spread in the vascular network, are known as pulse wave.

Pulse wave transmitting characteristics are closely linked with the hemodynamic parameters of the blood circulation system. Changes in pulse waveform characteristics are an important basis to evaluate the physiological and pathological state of the human cardiovascular system. When the pulse wave spreads from the heart to the arterial system, it is not only affected by the heart itself, but also by various physiological factors that flow through all artery and its branches, such as vascular resistance, vessel wall elasticity, the pulse wave contains very rich physiological and pathological information in cardiovascular system, so that whether Chinese pulse-taking or Western cardiovascular tests is tried to extract a variety of physiological and pathological information from the pulse waveform and pressure's changes. Therefore, the pulse wave transmitting studies are combined with the clinical testing and the pathological diagnosis in order to use non-invasive detection to analyze and diagnose the cardiovascular disease, will play a very important practical effect [1-12].

This paper proposed a solving method that cardiovascular function parameters K-value will be calculated based on the averaging method, according to changes of the area and waveform of the pulse in different physiological and pathological conditions, combined the K value with the pathological and diagnostic analysis.

II. WAVE DIAGNOSTIC PRINCIPLES BASED ON BLOOD FLOW

A. The Formation of Arterial Pulse Wave

The driving force of the blood circulatory system is the heart of the ejection, which the ventricle play a major role, it is usually called the cardiac cycle, in fact, refers to the movement cycle of the ventricle. Arterial blood pressure is the driving force that promotes blood to flow; it must reach a certain height in order to ensure the blood supply for all over organ. The process formed the arterial pulse wave that the arterial pressure transmits from the aorta to the small blood vessels and capillaries, which changes periodically into the cardiac cycle [11].

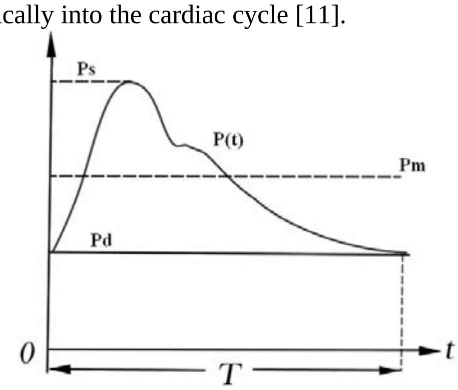

Figure 1. Pulse waveform coefficient K.

The typical pulse wave is shown in figure 1, it can be a good reflection of cardiovascular information system, if the body abnormal occurs (such as atherosclerosis, etc.), the arteries' nature will change, so pulse waveform changes must also occur.

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B. Cardiovascular Function Parameters K Computing Based on Pulse Wave

Needless to say, the characteristic information of pulse wave is closely related with the physiological factors. To study the relationship each other, many researchers get information from the time domain or frequency domain characteristics based on pulse wave in clinical trials or model. In the time domain, usually the pulse extracts some point with a clear physical meaning (such as the main wave peak, heavy pump wave height, etc.). The combination with the characteristic points and the corresponding physiological factors may get much clinical value. Some researchers have used simulation models to measure pulse wave different model parameters, to determine the person's physical condition according to different parameters. Facts have proved that this method is more effective, but the simulation models and the extracted characteristic parameters must be proper, can effectively distinguish the pathological state.

In many studies, because the extracted parameters are too complicated to make the distinction between pulse waves, it often occurs the misjudging phenomenon. Therefore, the extraction of the pulse wave parameter is the critical research. Professor Luo Zhichang used the existing two-chamber model of elastic wave pulse to extract the characteristics of K (called form factor) which represents changes of the pulse wave’s area [11]. Through the model theoretical analysis, thousands of animal experiments and clinical testing with different age’s healthy people and patients with cardiovascular disease, confirmed that caused the pulse wave map features and the corresponding changes in the area by physiological and pathological cardiovascular changes, and then reflect on the changes in K value. Determine the body's physical condition with the K value, although it can not achieve accurate quantitative analysis, but a simple calculation, differentiation, and the advantages of high sensitivity, which is important in the clinical reference value, is an important physiological indicators of the cardiovascular clinical examination.

The K value reflects the characteristic quantities which changes in the amount of area of the pulse wave [11], which is defined as the average of the relative position of the pulse wave, which is defined by type (1) and figure 1.

$$K = \frac{P_m - P_d}{P_s - P_d}. \quad (1)$$

where K is the form factor; P_m is mean arterial pressure, P_d is the diastolic blood pressure; P_s is the systolic blood pressure.

Thus, the form factor K value have nothing to do with the absolute value of systolic and diastolic blood pressure, it only depends on wave map area of the pulse wave, is a dimensionless parameter. Pulse waveform and area will have a great change in different physiological and pathological conditions, these changes can be expressed as K value.

Because the pulse wave is difficult to accurately measure and solve, this paper propose a solution based on the averaging method that K value of the pulse wave can be computed, and then through the specific network simulation of the cerebral circulation, the results is coincided with clinical measurement.

III. Cardiovascular Network Hemodynamic Analysis and Averaging Computation

According to the aforementioned study, in order to solve the pulse wave of blood circulation network diagram, first, analyze its network model [12-18]. In order to build blood circulation network's model, at first establishes the dynamic equation of one blood vessel branch. For simplicity, we make the following assumptions: Al. the blood is incompressible; A2.the temperatures in all branches are identical. Under assumptions Al and A2, one branch of the blood network is described with the following equations [12-18]:

$$\begin{aligned} T_j \frac{dQ_j}{dt} &= -R_j \left|Q_j\right| Q_j + H_j \\ T\dot{Q} &= -Q_D^2 R + H \end{aligned}. \quad (2)$$

where Q_j is flow through a branch j , R_j are hemodynamic resistances, H_j are pressure drops of the branches, $Tj = \rho l_j / S_j$ are inertia coefficients, $j = 1, \cdots, n$ and n is the number of network branches (excluding the generator branch). $T = diag\{T_j\}$, $R = col\{R_j\}$ and

$$Q_D^2 = diag\{Q_j \left|Q_j\right|\}. \quad (3)$$

Let n_c denote the number of nodes. Then $l = n - n_c + 1$ is the number of links (excluding the generator branch) and $n - l$ is the number of tree branches.

Like an electrical network, a fluid network must satisfy Kirchhoff's current law, i.e., the flow out of any node is equal to the flow into that node. Mathematically, Kirchhoff's current law for fluid flow networks can be expressed as:

$$E_{Qin} \begin{bmatrix} Q_{in} \\ Q \end{bmatrix} = 0 \text{ or}$$

$$\sum_{j=1}^{n} E_{Qij} Q_j + e_{Qin_i} Q_{in} = 0, \; i = 1, \cdots, n - l. \quad (4)$$

where $n - l + 1$ is the number of nodes (of which one is a “reference” node), Q is a vector of flows, $E_{Qin} = [e_{Qin} \; E_Q]$, and $E_Q = [E_{Qij}]$ is a full rank matrix of order $(n - l) \times n$ where $E_{Qij} = 1$ if branch j is connected to node i and the flow goes away from node i , $E_{Qij} = -1$ if it goes into node i , $E_{Qij} = 0$ if branch j is not connected to node i ; e_{Qin} is an $(n\text{-}l)\times 1$ vector such that, if the generator is connected to node i and the flow goes away from node i then $e_{Qini} = 1$, if the flow goes into node i then $e_{Qini} = -1$, and $e_{Qini} = 0$ if the generator is not connected to node i.

Similarly, the network satisfies Kirchhoff's voltage law, i.e., the sum of the pressure drops around any loop in the network must be equal to zero, or mathematically

$$E_H H = 0 \text{ or}$$

$$\sum_{j=1}^{n} E_{Hij} H_j = 0, \quad i = 1, \cdots, l, \tag{5}$$

where H_j is the pressure drop of the branch j, H is a vector of pressure drops, $E_H = [E_{Hij}]$ is an $l \times n$ mesh matrix, in which each mesh (loop) is formed by a link and a unique chain in the tree connecting the two nodes of the link. The elements of E_{Hij} are defined as follows: $E_{Hij} = 1$ if branch j is contained in mesh i and has the same direction, $E_{Hij} = -1$ if branch j is contained in mesh i and has the opposite direction, $E_{Hij} = 0$ if branch j is not contained in mesh i.

In order to establish a dynamic model of minimal order, one has to find independent variables as states of the system. We take the flows of link (co-tree) branches as state variables. If regards one time heartbeat as one period T, decomposes the blood pressure wave $f(t)$ into each kind of simple harmonic wave combination, that is:

$$\begin{aligned} Q_{in}(t) &= Q_0 + \left(\sum_{k=1}^{n} a_k \sin(\frac{2\pi k}{T} t + \phi_k) \right) \\ &= Q_0 + \sum_{k=1}^{n} a_k \sin(k\omega t + \phi_k) \end{aligned} \tag{6}$$

For convenience of analysis, we label the link branches (except the generator branch) from 1 to *l*. Define

$$Q = \begin{bmatrix} Q_c \\ Q_a \end{bmatrix}, \ H = \begin{bmatrix} H_c \\ H_a \end{bmatrix} \tag{7}$$

so that Q_c and H_c vectors describe flow and pressure drop, respectively, in the links, excluding the generator branch, and Q_a and H_a vectors describe them in the tree branches.

The matrices E_H and E_Q in can be split into blocks

$$E_H = \begin{bmatrix} E_{Hc} & E_{Ha} \end{bmatrix} \tag{8}$$

$$E_{Qin} = [e_{Qin} \quad E_{Qc} \quad E_{Qa}] \tag{9}$$

where [18-19]

$$E_{Qa} = I_{(n-l)\times(n-l)}, \ E_{Hc} = I_{l\times l}, \ E_{Ha} = -E_{Qc}^T \tag{10}$$

Hence, the structure of the network can be expressed in the matrix form as

$$E = \begin{bmatrix} 0 & I & -E_{Qc}^T \\ e_{Qin} & E_{Qc} & I \end{bmatrix} \tag{11}$$

Furthermore,

$$T = \begin{bmatrix} T_c & 0 \\ 0 & T_a \end{bmatrix}, \ R = \begin{bmatrix} R_c^T & R_a^T \end{bmatrix}^T \tag{12}$$

Fluid circulation through the network of network modeling, according to the aforementioned study, using the average method can solve the flow waveform, and then find its pulse wave flow waveform[15-20], that is:

$$\begin{aligned} \overline{Q}_c(t) &= Q_{c0} - \left(\sum_{k=1}^{n} \frac{a_k^2}{4} \right) V^{-1} U \\ &\quad + B_c \left(\sum_{k=1}^{n} a_k \sin(k\omega t + \phi_k) \right) \end{aligned} \tag{13}$$

$$\begin{aligned} \overline{Q}_a(t) &= (-E_{Qc} Q_{c0} - e_{Qin} Q_0) + \left(\sum_{k=1}^{n} \frac{a_k^2}{4} \right) E_{Qc} V^{-1} U \\ &\quad + B_c \left(\sum_{k=1}^{n} a_k \sin(k\omega t + \phi_k) \right) \end{aligned} \tag{14}$$

where

$$T_0(T) = T_c + E_{Qc}^T T_a E_{Qc} \tag{15}$$

$$U(R, T, E) = col\{B_{ci}^2 R_{ci}\} - E_{Qc}^T col\{B_{ai}^2 R_{ai}\} \tag{16}$$

$$V(R, E, Q_0) = diag\{Q_{c0i} R_{ci}\} - E_{Qc}^T W \tag{17}$$

$$W = \{E_{Qcij}(-E_{Qci} Q_{c0} - e_{Qin_i} Q_0) R_{ci}\}_{(n-l)\times l} \tag{18}$$

and $Q_{c0}(R, E, Q_0)$ denotes *l*-dimensional solution of quadratic equation, that is:

$$Q_{c0D}^2 R_c - E_{Qc}^T diag\{(E_{Qci} Q_{c0} + e_{Qin_i} Q_0)^2\} R_a = 0 \tag{19}$$

such that V is nonsingular and $-T_0^{-1} V$ is Hurwitz. Then for a given $Q_0 > 0$, for sufficiently small a and sufficiently large ω the solutions of the system (1) ~ (6) locally exponentially converge to a $O(1/\omega + a^4)$ neighborhood.

IV. Pulse Wave K Value Simulation and Clinical Pathological Diagnosis

A. Healthy Middle-aged Clinical Detection and Pulse Wave Simulation Analysis

To observe the relationship between the clinical value of K changes and the major physiological factors (such as the hardening degree of the blood vessel wall, peripheral resistance, etc.). First we measured the pulse waveform to a thousand patients with different age groups, including healthy people and people with varying degrees of high blood pressure or vascular sclerosis. The instrument is used with cardiovascular blood flow parameters TP-CBS detector. After statistical analysis, the typical waveform and the corresponding coefficient K are shown in Figure 2.

After measurement and clinical trials, the results showed that:

(1) Young and healthy people, pregnant women, athletes are low vascular resistance, arterial elasticity, the K value is about 0.33 (Figure 2 (a));

(2) Healthy young people in the vascular resistance and arterial elastic are medium, the K value between about 0.34 to 0.39 (Figure 2 (b), (c), (d), (e));

(3) Middle aged and elderly people are higher vascular resistance, poor arterial elasticity, the K value is about 0.4 or so (Figure 2 (f));

(4) Patients with severe hypertension and atherosclerosis are high vascular resistance, poor arterial elasticity, the K value is about 0.45 to 0.5 (Figure 2 (g), (h)).

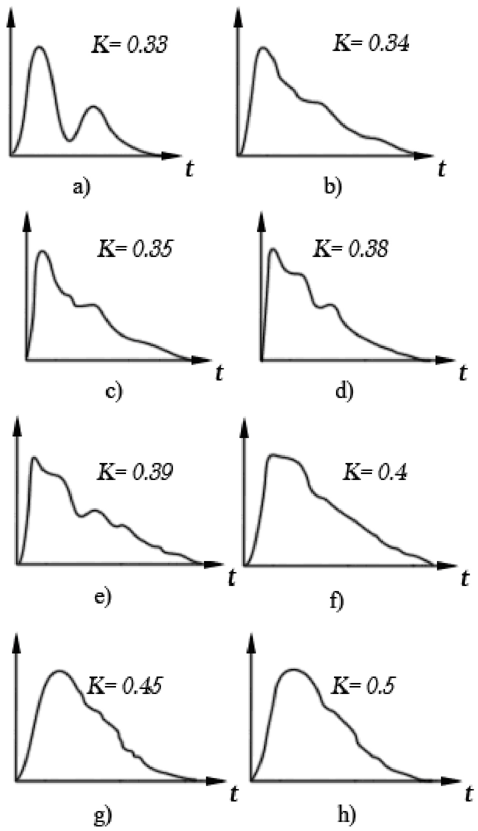


Figure 2. Pulse waves and K of people in different ages and healthy conditions.

Thus, increased with age or the development of hypertension, atherosclerosis, vascular resistance, pulse wave waveform develops bread-type waveform by the steep progressive, the waveform coefficient K increases correspondingly (in general changes between 0.35 ~ 0.5). It is shown in figure 3, maps of K values in the different age groups

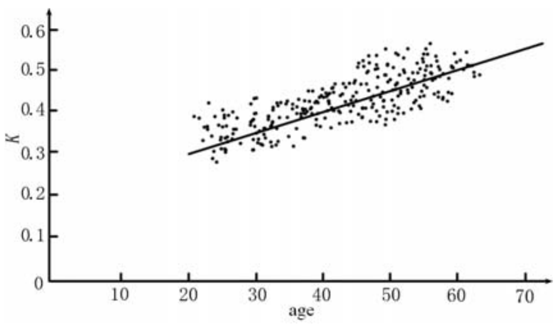


Figure 3. Maps of K values in the different age groups

Generally we measured radial artery pulse wave, because of its high flow, it is easy to measure, but considering that the circulatory system is large and complex, its model is difficult to solve, because the arterial pulse wave is constant in the transmission cycle, Therefore, we use the above method to solve cerebral circulation network.

Cerebral circulation refers to the movement of blood through the network of blood vessels supplying the brain. The arteries deliver oxygenated blood, glucose and other nutrients to the brain and the veins carry deoxygenated blood back to the heart, removing carbon dioxide, lactic acid, and other metabolic products. Since the brain is very vulnerable to compromises in its blood supply, the cerebral circulatory system has many safeguards. Failure of these safeguards results in cerebrovascular accidents, commonly known as strokes. The amount of blood that the cerebral circulation carries is known as cerebral blood flow.

Cerebral arteries describe three main pairs of arteries and their branches, which irrigate the cerebrum of the brain. The three main arteries consist of the: Anterior cerebral artery (ACA), Middle cerebral artery (MCA), Posterior cerebral artery (PCA). Both the ACA and MCA originate from the cerebral portion of internal carotid artery, while PCA branches from the intersection of the posterior communicating artery and the anterior portion of the basilar artery. The three pairs of arteries are linked via the anterior communicating artery and the posterior communicating arteries. All three arteries send out arteries that perforate brain in the medial central portions prior to branching and bifurcating further. Anatomy of the cerebral circulation is shown in figure 4, the cerebral circulation equivalent plane structure (18 branches) is shown in figure 5.

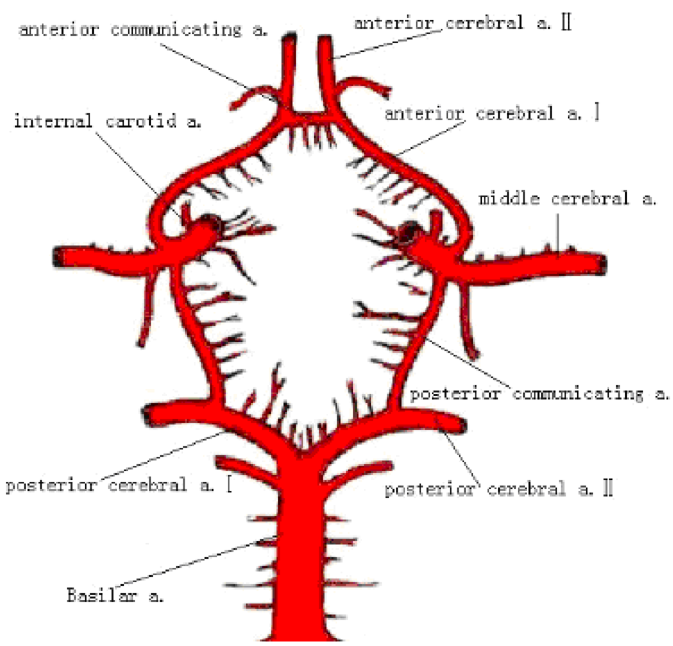


Figure 4. Anatomy of the cerebral circulation.

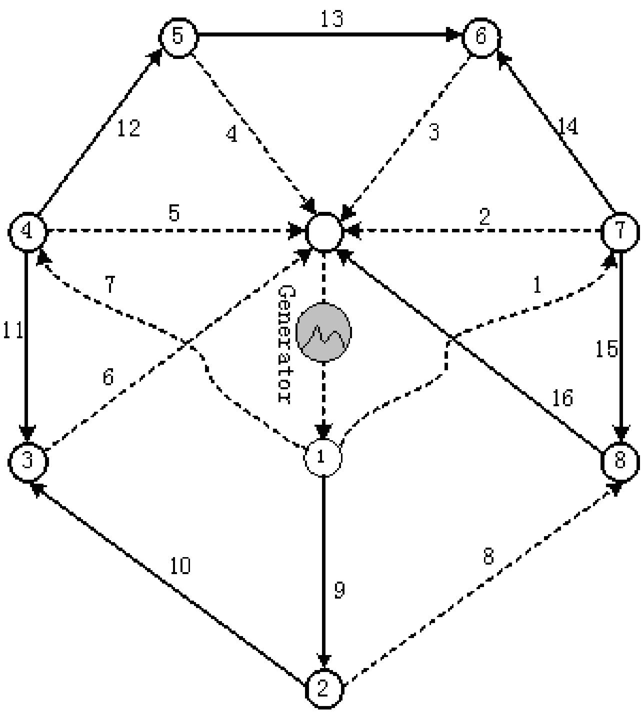


Figure 5. The network equivalent plane diagram of cerebral circulation (16 branches).

The network of the cerebral circulation has 16 branches, 8 nodes and 1 generator branch. Choose branches 9 to 16 and generator as the tree of the network. The node equations can be expressed as:

Node 1: $Q_{in} - Q_1 - Q_7 - Q_9 = 0$;

Node 2: $Q_8 + Q_{10} - Q_9 = 0$;

Node 3: $Q_6 - Q_{10} - Q_{11} = 0$;

Node 4: $Q_5 - Q_7 + Q_{11} + Q_{12} = 0$;

Node 5: $Q_4 - Q_{12} + Q_{13} = 0$;

Node 6: $Q_3 - Q_{13} - Q_{14} = 0$;

Node 7: $Q_2 + Q_{14} + Q_{15} - Q_1 = 0$;

Node 8: $Q_{16} - Q_8 - Q_{15} = 0$;

After transformation:

$Q_{in} = Q_1 + Q_7 + Q_9$

$Q_{in} = Q_1 + Q_7 + Q_8 + Q_{10}$

$Q_{in} = Q_1 + Q_6 + Q_7 + Q_8 - Q_{11}$

$Q_{in} = Q_1 + Q_5 + Q_6 + Q_8 + Q_{12}$

$Q_{in} = Q_1 + Q_4 + Q_5 + Q_6 + Q_8 + Q_{13}$

$Q_{in} = Q_1 + Q_3 + Q_4 + Q_5 + Q_6 + Q_8 - Q_{14}$

$Q_{in} = Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_8 + Q_{15}$

$Q_{in} = Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_{16}$

The loop equations can be expressed as:

Loop 1: $H_1 - H_9 - H_{10} - H_{11} + H_{12} - H_{13} - H_{14} = 0$;

Loop 2: $H_2 - H_{15} - H_{16} = 0$;

Loop 3: $H_3 + H_{14} - H_{15} - H_{16} = 0$;

Loop 4: $H_4 - H_{13} + H_{14} - H_{15} - H_{16} = 0$,

Loop 5: $H_5 - H_{12} - H_{13} + H_{14} - H_{15} - H_{16} = 0$,

Loop 6: $H_6 + H_{11} - H_{12} - H_{13} + H_{14} - H_{15} - H_{16} = 0$,

Loop 7: $H_7 - H_9 - H_{10} + H_{11} = 0$,

Loop 8: $H_8 - H_{10} + H_{11} - H_{12} - H_{13} + H_{14} - H_{15} = 0$.

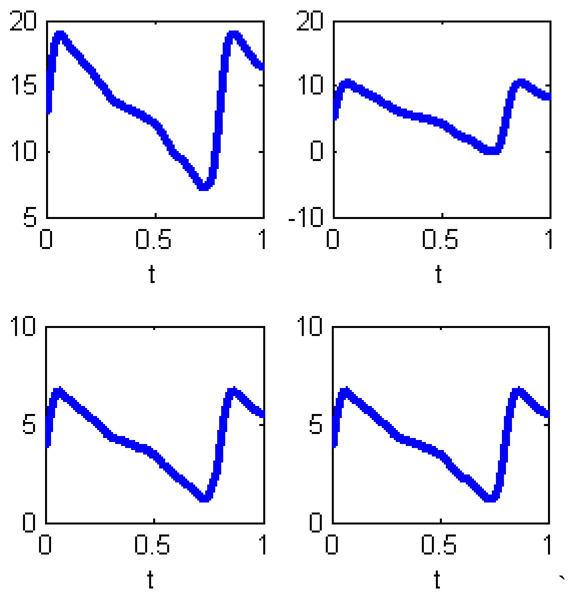
We knew l, d_1, ρ of the cerebral circulation network from paper [1], it is shown in table I.

TABLE I.
THE ARTERIAL GEOMETRY PARAMETERS OF THE CIRCLE OF WILLIS

artery	number	length(cm)	diameter(cm)
internal carotid a.	7,1	25	0.4
basilar a.	9	3	0.4
Posterior communicating a.	11,15	2	0.12
posterior cerebral a. Ⅰ	10,8	2	0.3
anterior cerebral a. Ⅰ	12,14	2	0.25
anterior communicating a.	13	0.5	0.15
middle cerebral a.	5,2	7	0.35
posterior cerebral a. Ⅱ	6,16	7	0.3
anterior cerebral a. Ⅱ	4,3	5	0.25

We can obtain T from $T = \frac{\rho l}{S}$ and R from $R = \frac{1.63 l}{D^4}$. We may obtain Q_{c0} equation set from type (19), this equation only has numerical solution, but does not have the exact solution, uses the genetic algorithm to get the iterative solution. We can get H from Q, H is equal to P.

First, we solve the cerebral circulation blood flow Q with the normal person, and we can get H from (2), that is P in (1), its computing simulation result is shown in figure 6.



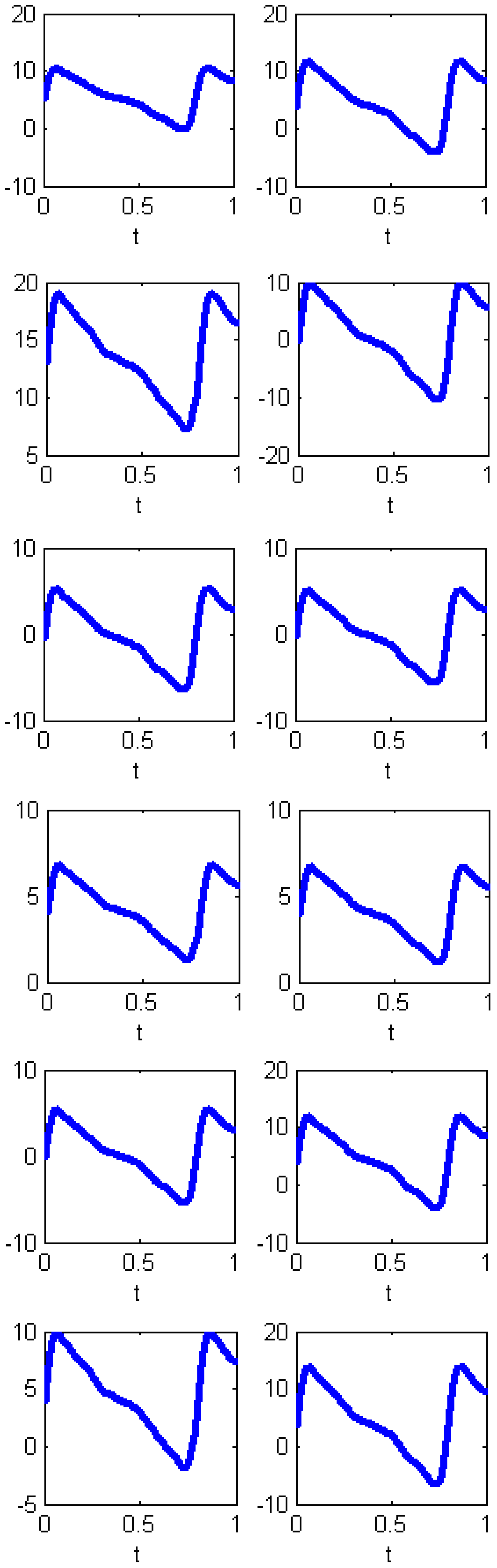


Figure 6. The circle of Willis pulse wave with the normal human.

It is shown in figure 6, the normal cerebral circulation network 10 times harmonic waveform are basically the same with healthy middle-aged in figure 2 and figure 3 , the K value is 0.356 by calculating, and K is clinically consistent with 0.34 ~ 0.39.

B. Cerebral Infarction Clinical Detection and Pulse Wave Pathological Analysis

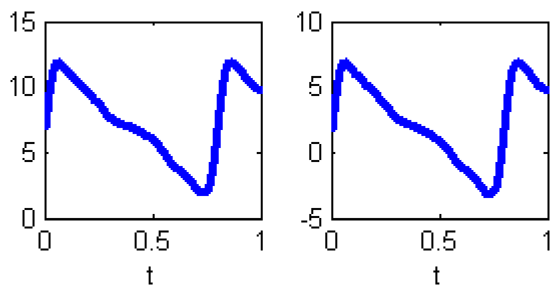
Cerebral infarction causes brain tissue partial arterial blood flows poorly or completely stop due to insufficient blood supply, and blood viscosity is an important factor in causing vascular resistance, and its dynamic changes are related with the cerebral lesions closely. From paper [11], in order to clarify the correlation between the waveform characteristic K value and the blood viscosity, in clinical test, the observed 100 cerebral infarction patients with CT or NMR diagnosis (mean age 54 years, male 63 cases, females 37 cases) are varying degrees of hyperviscosity and microcirculation. Before and after treatment, use blood flow parameters TP.CBS nondestructive detector to detect the patient's pulse wave pressure and K-value. At the same time, use LS30 to test blood viscosity, and compared with the K value, the results is shown in Table II.

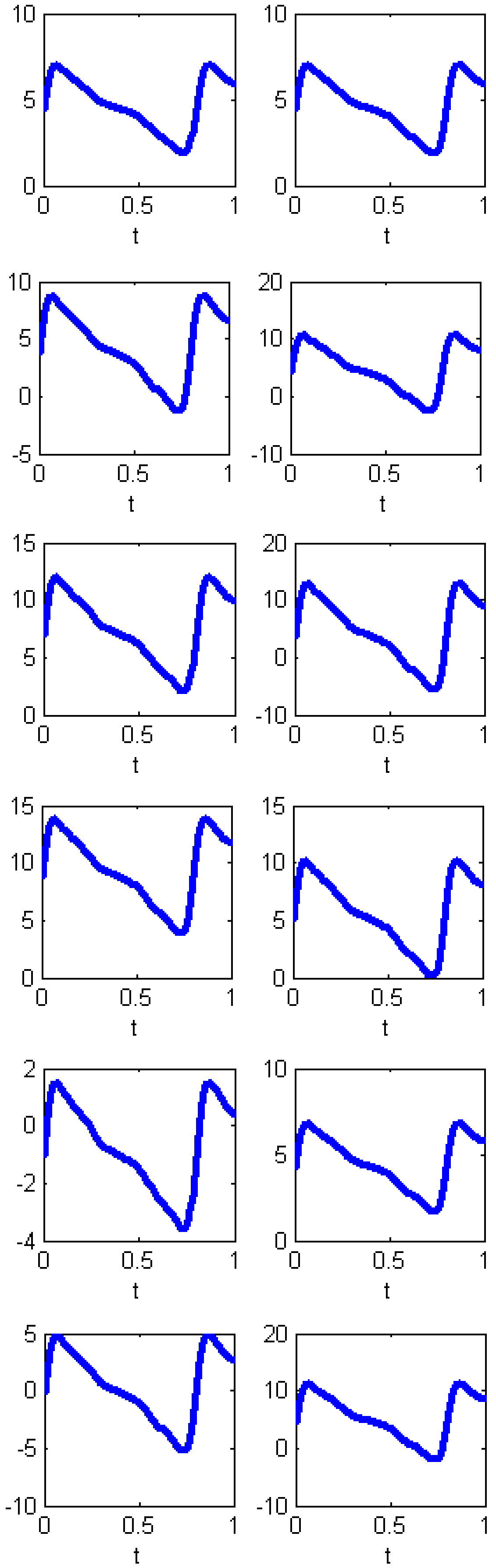
TABLE II.
CLINICAL EXAMINING RESULTS

Parameter	Before treatment	After treatment
K	0.55±0.12	0.31±0.1
Blood viscosity	6.27±1.9	3.6±1.2

Setting the terminal resistance value of R_2 that is 3 times higher than normal to simulate the side of the middle cerebral artery area infarction lesions, choose to simulate the case of compensatory cerebral calculation, select the compensatory situation in which the normal circle of Willis before and after the traffic artery open.

Taking the terminal resistance value of R_2 which is 3 times higher than normal to simulate the side of the middle cerebral artery area infarction lesions, choose the compensatory situation to simulate cerebral calculation, which the traffic arteries of the circle of Willis are open. Taking the diameter of the anterior communicating artery to calculate parameters, D13=0.2cm, the diameter of the posterior communicating artery $D_{11}=D_{15}=0.15$cm, R_{13}, R_{11}, R_{15} are 590, 6439 and 6439 dyn·s/cm, $T_{13}=119.4908$, we can get Ten harmonics from (13) and (14), The circle of Willis pulse wave with the cerebral infarction is shown in figure 7.





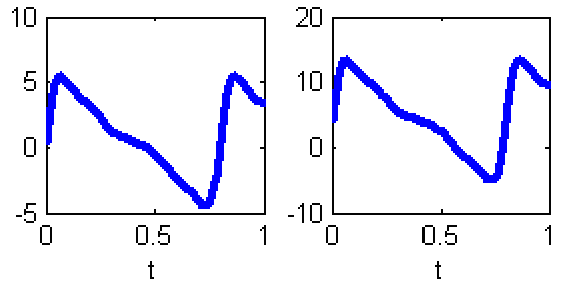


Figure 7. The circle of Willis pulse wave with the cerebral infarction.

We can see the pulse wave of the cerebral infarction from the simulation figure 6, the K value is 0.495, and is close to the clinical test of cerebral infarction in Table II, $K = 0.55 \pm 0.12$, from the changing trend of the K value, this result matches with the actual clinical detection basically.

V. Conclusion

In summary, the pulse waveforms extracted the K value by averaging computation and the wave area, although it does not fully reflect subtle changes in the pulse curve that contains all the local physiological and pathological significance, but it represents some important physiological parameters in the human blood circulatory system, such as peripheral vascular resistance, blood viscosity and so on. Considering the characteristic information to reduce only one characteristic quantity K, it is easy to remember, a clear physiological significance, and changes very regular, can be easily accepted by clinicians, so it can be used as important cardiovascular physiological parameters of the clinical examination.

In the averaging computing pulse wave process, the network only needs to know the relevant basic physiological parameters of blood vessel branch, and calculating the pulse wave and the K value is more high precision than pulse wave detector. The stability testing results do not affect with the emotional fluctuates in the waveform, the different K values corresponds to different pathological conditions, so that it can provide an non-destructive testing mathematical calculation and analysis methods for the clinical parameters of blood circulation.

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