A blood pressure measurement method based on synergetics theory

Hong-jin GUO, Jian-jun HAO, Ting WANG, Zhi-xin CHENG

(College of Information and Electronical Engineering, Shandong University of Science and Technology, Qingdao 266510, China)

Abstract—**The principle for blood pressure measurement using pulse transit time is introduced in this paper. And the math model of synergetics theory is studied in detail .The synergetics theory is applied in the analysis of blood pressure measurement data. The simulation results show that the application of synergetics theory is helpful to judge the normal blood pressure, and the accuracy is up to 80%.**

***Keywords*—pulse wave；synergetics theor；Blood pressure measurement**

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1 Introduction

Blood pressure is an important indicator of human body health. Hypertension, often accompanied by heart and vascular lesions will cause great harm to human body [1]. Blood pressure plays an important role in human body health, so the experts have been devoted to the blood pressure research work. Along with the development of modern science and technology, the modernization and objective research of blood pressure brings new vigour and vitality into traditional blood pressure measurement. How to objectively and accurately extract blood pressure signals and then process and analyse them is very important in clinical and medical research. In the clinical medicine, critically ill patients and patients with severe gravely ill in surgery need continuous blood pressure monitoring, so that medical staff can take appropriate lowering blood pressure measures and avoid missing the best treatment time. The patients can be timely diagnosed [2].

2 The theory of blood pressure measurement using pulse transit time

The pulse wave velocity refers to the propagation velocity of the pulse in vessel. It is determined by arterial vascular walls geometry characteristics (diameter and wall thickness), mechanical properties (viscosity and elasticity), vascular caliber size and the blood density [3] [4].

Suppose arteries are a uniform straight thin-walled elastic pipe, and is infinite long. It can be equated to uniform cross-section elastomer with radius naturally .Blood is the ideal cohesion less flow, and the pressure pulsation is small. So we can use linearization method to deal with it. Hill and Bramble modify the *Moens* - *Korteweg* formula, after much verification [5]:

$$C = \sqrt{\frac{V}{\rho(\partial V/\partial P)}} = \sqrt{\frac{V\partial P}{\rho\,\partial V}} \qquad (1)$$

where C is the pulse wave velocity, V is the blood volume. ρ is the blood density, P is the corresponding blood pressure. We regard ρ as constant; the formulas can be simplified as [6]:

$$\Delta P \propto c^2\left(\frac{\Delta V}{V}\right) \qquad (2)$$

So we choose pulse wave transmission time which both relates with the pulse wave velocity C and $\Delta V/V$ to calculate blood pressure.

After transmitting a certain distance, the pulse transmission time is in contrast with the pulse wave velocity. If we know one, then we can seek the other. S stands for pulse wave transmission distance; T stands for pulse wave transmission time, the relationship between them can be expressed as: $c=\frac{S}{T}$.

Pulse Transmission Time refers to the time that pulse transmits from arteries near the heart to another place far from the heart, that is the time that the Pulse transmits between two arterial [7][8]. For the same individual, Pulse Transmission Time and blood pressure is in a linear relationship within a certain range. We can indirectly calculate arterial blood pressure by measuring the Pulse Transmission Time and making using of the relationship between PTT and blood pressure.

PTT is usually expressed by the time between R wave characteristic point and pulse wave characteristic point in the same cardiac cycle. The electrocardiosignal and pulse signal in the same cardiac cycle are analyzed. The peak point of R wave

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Corresponding author: Hongjin Guo（guohongjin10@163.com)

is a starting point, the main peak point of pulse wave signal wave is the destination, the timing difference between them is the pulse wave transmission time [9] [10].

3 The synergetics theory

3.1 The introduction of synergetics theory

The synergetics theory is a set of method and theory processing non-equilibrium transformation proposed by German physicist H.Haken professor in 1977[11].It combined with catastrophe theory, the phase equilibrium mutation theory, information theory, the power system theory and the dissipative structure theory based on studying the laser.

The basic idea is [12]: the various subsystems in life and nonliving open systems are in disorder before the phase transition. And when the system is in a certain state in or far from the equilibrium state, it reaches a certain critical point, the critical undamped phenomenon appears. At this time synergy effect and coherent effect is generated by nonlinear interaction and make the system mutate from disorder to order. This causes the old structure changes to a new structure system in time, space, function and other aspects.

3.2 The mathematic model of synergetics

The evolution process of system containing a single variable or multivariable can be described by single differential equation or equations. The dynamic system with state elements q is mainly studied .If a system contains M components, the cooperative system can be expressed by the dynamics equations.

$$q = (q_1, q_2, ..., q_M) \tag{3}$$

According to the mathematics theory of synergetics, the state vector q evolutes along with time:

$$\dot{q}(x,t) = N[q(x,t), \nabla, \alpha, x] + F(t) \tag{4}$$

x is spatial coordinate, t is time coordinate, $\dot{q}(x,t)$ is the First derivative of q for time t, N is function vector determined by q , ∇ is differential operator, $\nabla = (\partial/\partial x, \partial/\partial y, \partial/\partial z)$, α is the control parameters of out constraint force, $F(t)$ is the fluctuating force. In some cases, $F(t)$ is decisive, but in many cases and it can be ignored.

According to the point of synergetics, when a system is driven only by external weak controlling force, there will be a state q0 independent of time and space, namely:

$$q_0(\alpha_0) \Rightarrow q_0(\alpha) \tag{5}$$

The control parameter changes from α_0 to α, the above state will change. We verify the stability under the assumption:

$$\alpha \Rightarrow q(x,t) = q_0 + w(x,t) \tag{6}$$

Ignoring the temporary fluctuation force, we making the (4) to the (6), and expand N to the power series of w in q_0.and we get:

$$N(q_0 + w) = N(q_0) + Lw + \hat{N}(w) \tag{7}$$

L is the matrix, $N(w)$ is the nonlinear function of w .Because q_0 is the non-static solution changing with α,

$$\dot{q}_0 = N(q_0) = 0 \tag{8}$$

After the liner stability analysis, the retaining is:

$$\dot{w} = Lw,\ L = L(L_{ij}) = (\partial N_i/\partial q_j \mid q = q_0) \tag{9}$$

The solution is:

$$w = e^{\lambda t} v(x) \tag{10}$$

Suppose

$$q = q_0 + \sum_j \xi_j(t) v_j(x) \tag{11}$$

And insert it into (4), we get:

$$\sum_j \dot{\xi}_j(t) v_j(x) = \sum_j \xi_j(t) L v_j(x) + \hat{N}\left[\sum_j \xi_j(t) v_j(x)\right] + F(t) \tag{12}$$

We can structure the adjoint function set：

$$\langle v_k^+ v_j \rangle \equiv \int v_k^+(x) v_j(x) dV = \delta_{kj},\ \delta_{kj} = \begin{cases} 1 & k = j \\ 0 & otherwise \end{cases} \tag{13}$$

And then we use the properties as follows:

$$\begin{aligned} &L v_j(x) = \lambda_j v_j(x) \\ &\int v_k^+(x) F(x,t) dV = F_x(t) \\ &\int v_k^+(x) \hat{N}\left[\sum_j \xi_j(t) v_j(x)\right] dV = N_k\left[\dot{\xi}_j(t)\right] \end{aligned} \tag{14}$$

And make integrations in space, the (12) transforms to:

$$\dot{\xi}_k = \lambda_k \xi_k + \dot{N}_k\left(\xi_j\right) + F_k\left(t\right), 1 \quad (15)$$

According to the real symbols type of λ_j there is two kinds of circumstance: if the real is negative, $v(x)$ is stability, If the real is non-negative, the corresponding configuration is unsteady mode. The evolution of the system is determined by unsteady mode (ξ) according to synergetics. So the sequence parameters of unsteady mode are discussed only.

4 Synergetics algorithm applying in blood pressure data fusion

When we fuse blood pressure data, sequence parameters is first structured by basic characteristics of blood pressure, blood pressure data fusion model is structured by nonlinear dynamic equation. The variables in the equation are divided into fast variables and slow variables using the adiabatic equivalence principle of synergetics. The fast variables is eliminated by slaving principle, the system can be expressed as low-dimensional equation with only a few slow variables, which is sequence parameter equation. The blood pressure monitoring process is regarded as sequence parameter dynamics system operation process. The final state is judged through studying evolution process of the sample in the system. We obtain analysis of the blood pressure dynamic characteristics and thus get the correct discriminate result.

Suppose the initial mode number of blood dynamic characteristics is M, the blood pressure recognition vector dimension is N, we require $M \le N$, so:

$$\dot{q} = \sum_{k=1}^{M} \lambda_k (v_k^+ q) v_k - B \sum_{k \ne k'} v_k (v_{k'}^+ q)^2 (v_k^+ q) - Cq(q^+ q) + F(t)$$

(16)

q is the state vector with the initial value $q(0)$.It is the archetypal mode needing to identify that influences blood pressure dynamic characteristic. λ_k is the attention parameter, only λ_k ≤0, the mode can be recognized. $F(t)$ is the fluctuation force, namely the external force or disturbance. B and C is the specified coefficient. v_k is the archetypal pattern vectors, $v_k = (v_{k1}, v_{k2}, ..., v_{kN})'$. v_k^+ is the adjoint vector of v_k, and meet :

$$(v_k^+, v_{k'}) = v_k^+ v_{k'} = \delta_{kk'} = \begin{cases} 1, k = k' \\ 0, k \ne k' \end{cases} \quad (17)$$

In addition, v_k must meet the normalized and zero mean conditions:

$$\|v_k\|_2 = (\sum_{l=1}^{N} v_{kl}^2)^{1/2} = 1, \sum_{l=1}^{N} v_{kl} = 0 \quad (18)$$

The equation in (16) can be described as the common dynamics equation, ignoring $F(t)$, we get potential function:

$$V = -\frac{1}{2}\sum_{k=1}^{M} \lambda_k (v_k^+ q)^2 + \frac{1}{4} B \sum_{k \ne k'} v_k (v_{k'}^+ q)^2 + \frac{1}{4} C \left(\sum_{k=1}^{M} (v_k^+ q)^2 \right)^2$$

(19)

We make recursion of ECG, Pulse condition, body temperature, blood pressure and other physiological parameters according to certain time step which will form a time sequence. The dynamic characteristics of blood corresponds archetypal mode q_i, archetypal mode and input time sequence constitute the initial value of order parameters according to the synergetics algorithm, which reflects the matching between the blood mode of the subjects and various archetypal blood pressure mode. Due to the complexity of the blood system, experts conduct comprehensive judgment and decision from actual conditions and in the basic dynamic characteristics.

We divide blood pressure mode vector q into archetypal blood pressure mode vector v_k and residual vector ω, we get:

$$q = \sum_{k=1}^{M} \xi_k v_k + \omega \quad (20)$$

It needs that $v_k{}^+ \omega = 0, k = 1, 2, ..., M$

We define the adjoint vector corresponding to $\dot{q}$,

$$q^+ = \sum_{k=1}^{M} \xi_k v_k{}^+ + \omega^+ \quad (21)$$

At the same time, $\omega^+ v_k = 0, k = 1, 2, ..., M$.

When we contrast the formula in (20) and (21), we can get: ${v_k}^+ q = q^+ v_k$ .Combining with the formula (20) according to the orthogonal relation, we get

$$\xi_k = {v_k}^+ q = q^+ v_k \tag{22}$$

We contrast formula in (3.4) and (3.7), we get the dynamics equation of ξ_k :

$$\dot{\xi}_k = \lambda_k \xi_k - B\sum_{k' \neq k} \xi_{k'}^2 \xi_k^2 - C(\sum_{k'=1}^{M} \xi_{k'}^2)\xi_k \tag{23}$$

And it obeys the relations as follows:

$$\dot{\xi}_k = \xi_k(\lambda - D + B{\xi_k}^2) \ D = (B+C)\sum_{K'} {\xi_{K'}}^2 \tag{24}$$

Furthermore, the initial condition is

$$\xi_k(0) = v_k^+ q(0) \tag{25}$$

The stability of blood pressure measurement system is determined by:

$$\dot{\xi}_k = 0, 1 \le k \le M \tag{26}$$

That is,

$$\lambda_k \xi_k - B\sum_{k' \neq k} \xi_{k'}^2 \xi_k - C(\sum_{k'=1}^{M} \xi_{k'}^2)\xi_k = \xi_k(\lambda_k - D + B\xi_k^2) = 0 \tag{27}$$

In the blood pressure model evolution process, ξ_k represents the mutual competition between different blood pressure estimate models, the winning order parameter is the recognized archetypal mode. According to (27) ξ_k is gradually evolved, until the evolution process is stable. The evolution formula is as follows, γ is the iteration step length.

$$\begin{aligned} &\xi(n+1) - \xi(n) = \gamma(\lambda_k - D + B\xi_k^2(n))\xi_k \\ &D = (B+C)\sum_{k'} \xi_{k'}^2(n) \end{aligned} \tag{28}$$

$\xi_k(t)$ evolutionary stable is projected to output layer as below formula. We get several corresponding dynamic characteristics of blood pressure .thus complete the blood pressure judgment based on synergetics.

$$q_l(t) = \sum_{k=1}^{M} \xi_k(t) v_{lk} \ , l = 1, 2, \ldots, N \tag{29}$$

According to the analysis above, the implementation procedure is:

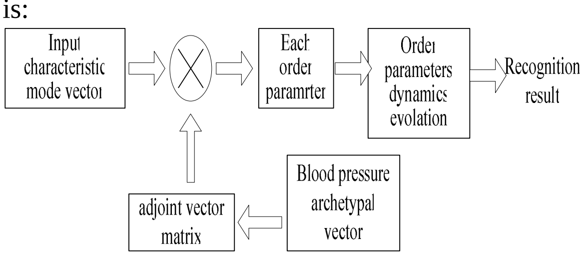

Fig.1 Recognition process of blood pressure based on Synergetic

5 Synergetics algorithm simulation

In order to verify the accuracy of our design, we selected 10 subjects from healthy people, patients with pre-hypertension, hypertensive patients. And test their systolic pressure and diastolic pressure.

We adopt ECG, temperature data from the three groups, and make data fusion algorithm simulation. In the laboratory, in order to accurately reflect the co-evolution test results, we use sequence parameter variation to reflect the test results.

λ_k should equal and are set to 1so our simulation is under the balance attention parameter condition. We choose proper values for B , C , γ .We set $B = C = 1$ to guarantee each mode of the system is convergent. We set $\gamma = 1/D$ .and adaptive adjusting step, which can make the sequence parameter curves steady and rapid converge.

Figure 2, figure 3, and figure 4 are the corresponding blood pressure recognition result of a typical individual from normal people, pre-hypertension patients, hypertension patients and ξ_k value variation process during the algorithm implementation. The horizontal axis is iteration steps, vertical axis is ξ_k value.

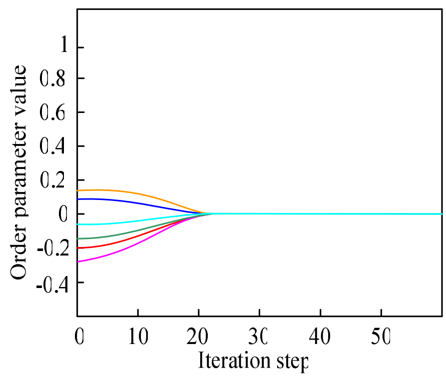

Fig. 2 Evolutionary Process of Health's ξ_k

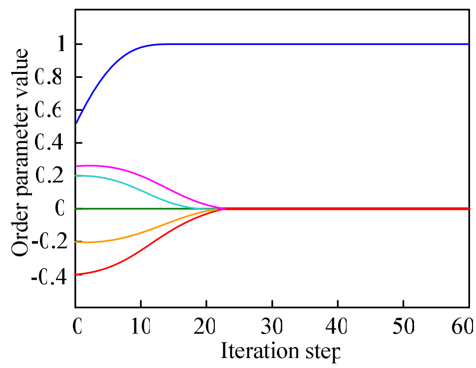

Fig.3 Evolutionary Process of Pre-Hypertensive People's ξ_k

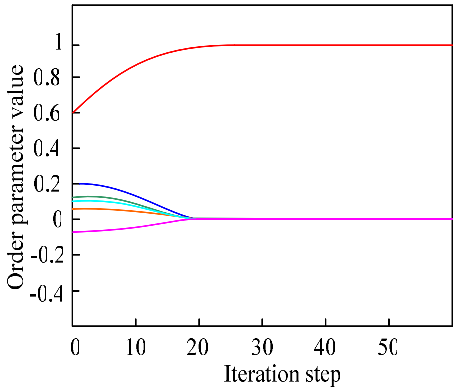

Fig.4 Evolutionary Process of Hypertensive People's ξ_k

In Fig.2, all order parameters are 0 finally. That indicates that blood pressure mode of the subject is not any of the blood pressure archetypal dynamic model. So the blood pressure is normal.

In Fig.3, blue curve is dipper hypertension archetypal mode. We can see that with the iteration after about 18 steps. Only the biggest order parameter with initial value 0.5 can increase tend to 1, and becomes the wining order parameter. The corresponding v_k is the wining archetypal mode recognized. The other sequence parameter gradually attenuate tends to 0.

In Fig.4, the red curve is non-dipper hypertension archetypal mode. After about 20 iterative steps, the sequence parameter with initial value 0.6 wins. The other sequence parameters attenuate tends to 0.so wee can judge blood pressure characteristics correctly.

We collect all the data and simulate, the simulation result is shown in table1.

Tab.1 Distinguish result of blood pressure data fusion

Groups	The number of subject	The correct number	recognition rate
Three	30	26	86.7%
Health	10	9	90%
Pre-Hypertensive	10	8	80%
Hypertensive	10	9	90%

6 Conclusions

From the analysis of simulation results we can see that synergetics data fusion algorithm can get rid of measurement errors of various factors. After a gradual iterative evolution, variables not suitable for identification will be picked, finally the parameters with the strongest discrimination will remain to match with blood pressure dynamic characteristic. Blood pressure state is judged. The accuracy is up to 80% .It can realize the first judgment. However, the experimental subjects are limited and experimental method has some shortcomings. The test results above are not authoritative; the performance of the system needs further verification.

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(From P.159)

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