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Low Cost Human Pulse Wave Velocity Automated Measuring Device

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Abstract: Arteriosclerosis evaluation is essential for the clinical diagnosis of cardiovascular disease. Pulse Wave Velocity (PWV) is considered as the independent predictors of assessing arterial stiffness. Basing on the principles of PWV measurement and equivalent electric circuit model of artery, we designed a low cost noninvasive human pulse wave velocity measuring device. Its clinical experiment involving 123 subjects was carried out. The device can acquire pulse wave signals by means of a self-made measurement circuit and PWV is calculated by custom-designed software based on LabVIEW. Clinical experiment shows that PWV can reflect the differences between hypertension and normal blood pressure. In addition, of the 123 subjects, 27 were detected by this device to have a tendency of artery hardening, 23 of them were validated by Doppler ultrasound diagnostic device. The conformity of the two methods was up to 85.16%. This study verified the validity and reliability of the device.

Key words: Pulse wave velocity, arteriosclerosis, electronic medical equipment, noninvasive detecting, LabVIEW

INTRODUCTION

Cardiovascular disease is the leading cause of death in most industrialized countries, the incidence and mortality of which are mainly caused by artery lesions. Researches have shown that artery lesions tend to be asymptomatic at early stages when decreasing in vascular-wall elasticity and arteriosclerosis are already well on the way. It has been proved by a large number of epidemiological studies and clinical trials that increased arterial stiffness is an independent risk factor of cardiovascular disease (Zaman *et al*., 2008). So, detecting changes in arterial stiffness at the early stages of atherosclerosis would not only be of great value for prevention and treatment of cardiovascular disease but also provide references for its diagnosis.

Technologies have made considerable progress in non-invasive detection of arterial stiffness, among which, Pulse Wave Velocity (PWV) has already been widely used in clinical tests and epidemiological studies for its simplicity, accuracy and reproducibility (Cohn, 2006; Takenaka *et al*., 2004). At present, three techniques-Doppler Ultrasonography, Magnetic Resonance Imaging (MRI) and Pulse Waveform Analysis-are used chiefly in measurement of PWV. Doppler ultrasound technology is widely used in clinical tests (Laurent *et al*., 2006; Tillin *et al*., 2007) but its shortage in accurately measuring the distance between two sensors would lead to higher PWV results, besides, it can only evaluate central aortic PWV indirectly (Karamanoglu, 2003). Several MRI-based methods have been used to measure PWV, including 1D MRI measurement techniques (Bock *et al*., 1995), flow-area methods (Laffon *et al*., 2005), correlation of second-order derivatives of the velocity waveforms (Urchuk and Plewes, 1995) and transit-time method (Fielden *et al*., 2008). Pulse waveform analysis can achieve PWV measurement fast and with relatively low cost. At present, two devices using different measuring method for transit time are commonly used to calculate carotid-femoral PWV, namely Complior (Artech) and SphygmoCor(AtCor). The foot-to-foot algorithm and the maximum slope algorithm are applied in the first device and the second one, respectively (Millasseau *et al*., 2005). Sola *et al*. (2011) developed a waveform-based method that gets the chest PWV by measuring central arterial Pulse Transit Times (PTT) with a chest sensor. This approach used a combination of thoracic impedance cardiography and phonocardiography to measure Pre-ejection Period (PEP) and multichannel reflective photoplethysmography attached to sternum to measure

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the distal Pulse-arrival Time (PAT). And PTT values were calculated by Equation:

$$\text{PTT} = \text{PAT-PEP}$$

The present devices for measuring PWV have the bulk is big, the price is high, the operation is complicated, do not suit for use in the home. Due to solve the problem, this study proposed a low cost portable pulse wave velocity measuring device which is based on microprocessor and LabVIEW.

MATERIALS AND METHODS

In this study, basing on the equivalent electric circuit model of artery and principles of PWV measurement, we designed the measurement circuit and analyzing software written in LabVIEW and designed experiments to assess the performance of this device.

Equivalent electric circuit model of artery: Equivalent electric circuit model of artery is based on the cardiovascular dynamics and fluid network theory. It proposes an analogy of various parameters between fluid network and electric circuit by comparing hydraulic transmission system of compliant tubes and electrical transmission line (John, 2004). Such model uses a limited number of discrete components to simulate the distributed properties of cardiovascular system, making hydraulic resistance equivalent to resistances, blood stream equivalent to current, blood pressure equivalent to voltage, inertia of blood in arterial vessel equivalent to inductances, arterial compliance equivalent to capacitances. This study will present the electric circuit model for upper extremity in three parts: part 1 for the front end of brachial artery (near the elbow joint), part 2 for the whole of radial artery and part 3 for peripheral artery of the hand. The electric circuit model is shown in Fig. 1. Where, R_b and R_R are hydraulic resistances of the brachial artery and the radial artery, respectively; L_b and L_r are inertia of blood of the brachial artery and the radial artery, respectively; C_b and C_r are arterial compliance of the brachial artery and the radial artery, respectively; R_{p1}, R_{p2} and C_p represent parameters of palm.

Principle of PWV measurement: In theory, Bramwell-Hill equation (Eq. 1) demonstrates that PWV is inversely related to the square root of the distensibility of the blood vessels; the higher PWV, the stiffer the blood vessels. Similarly, if the blood vessel is regarded as a thin-walled linear elastic tube, Moens-Korteweg equation (Eq. 2) demonstrates that PWV is directly proportional to the square root of the Young elasticity modulus (E) but that PWV is also determined by the geometry of blood vessels (Segers *et al*., 2009):

$$\text{PWV} = \frac{1}{\sqrt{\rho DC}} \tag{1}$$

$$\text{PWV} = \sqrt{\frac{Eh}{\rho D}} \tag{2}$$

In these formulas, ρ is the density of the blood, DC is the distensibility of the blood vessels, h is the wall thickness of the vessel and D is diameter of the vessel.

In practical engineering, we placed two pressure sensors at the wrist radial artery and brachial artery, respectively to detect the pulse wave. The distance (D) between the center of two sensors and the time (Δt) it took for a pulse to travel between the two sensors were measured. And PWV was calculated by Eq. 3:

$$\text{PWV} = \frac{D}{\Delta t} \tag{3}$$

Hardware design: The hardware of the device is mainly composed of the circuit of analog signals processing, the

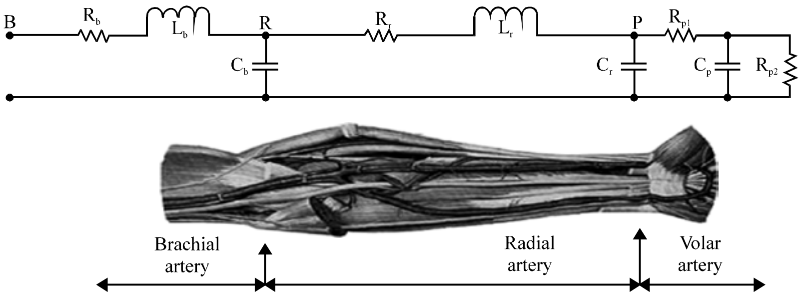


Fig. 1: Equivalent electric circuit model of artery

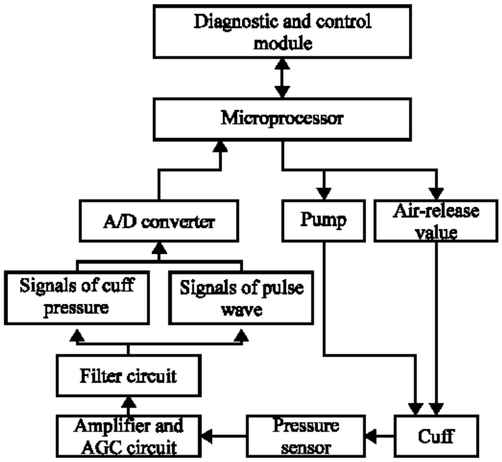


Fig. 2: Hardware architecture of the device

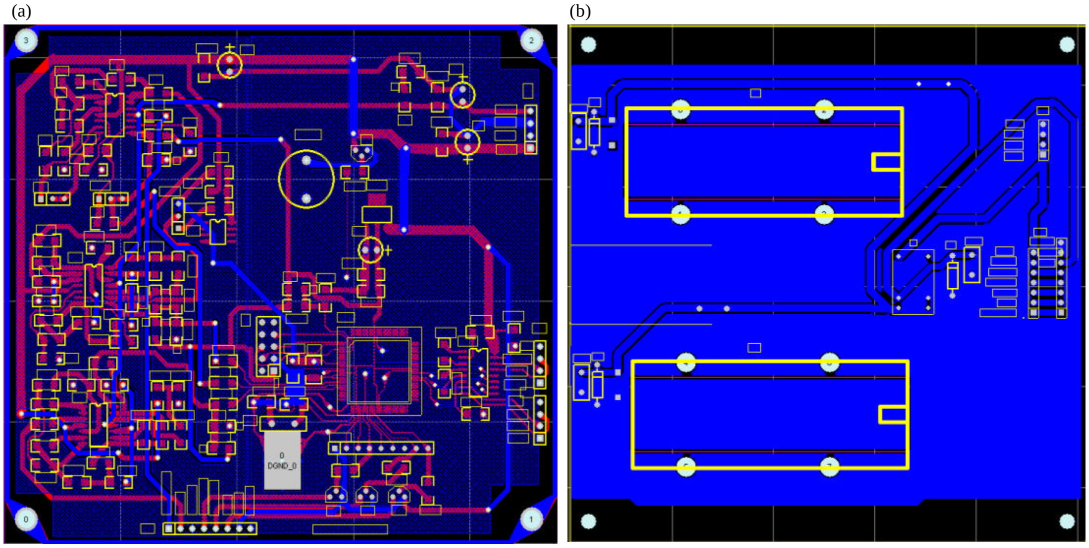


Fig. 3(a-b): Layout design of the device, (a) Main circuit board and (b) Inflation deflation controller circuit board

digital circuit and the circuit of inflation/deflation controller. The hardware architecture and the layout design of the device are shown in Fig. 2 and 3, respectively.

Through human pulse detection, it is convenient for people to estimate physical condition of our body (Nomura *et al*., 2012). An adult cuff and a baby cuff were used to measure brachial artery and radial artery pulse wave signal, respectively. First, both cuffs were inflated with an air pump under the control of a microcontroller until the arteries stopped pulsating due to the pressure, then a discharge valve slowly deflated the cuffs under the control of the microcontroller as programmed, gradually releasing the pressure. When the cuff pressure dropped below the systolic arterial pressure, brachial artery and radial artery began to pulsate more and more strongly as the cuff pressure decreased. The pulse wave signal acquired by the pressure sensor was actually a mixed-signal containing cuff pressure signal and other noises. This signal was first converted into voltage signal by the pressure sensor, amplified and filtrated with a 0.6-6.4 Hz band-pass filter to get the desired pulse wave signal required to calculate PWV; then the analog signal was converted into digital one with an A/D circuit and uploaded into a host computer via the serial interface, where the final analysis was made with a diagnostic/control module and results were displayed.

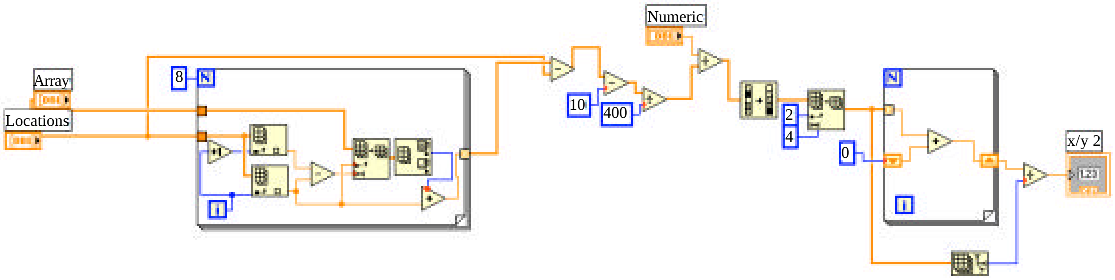


Fig. 4: Block diagram of algorithm of PWV

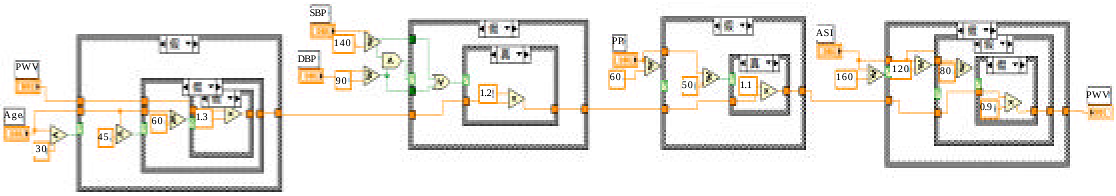
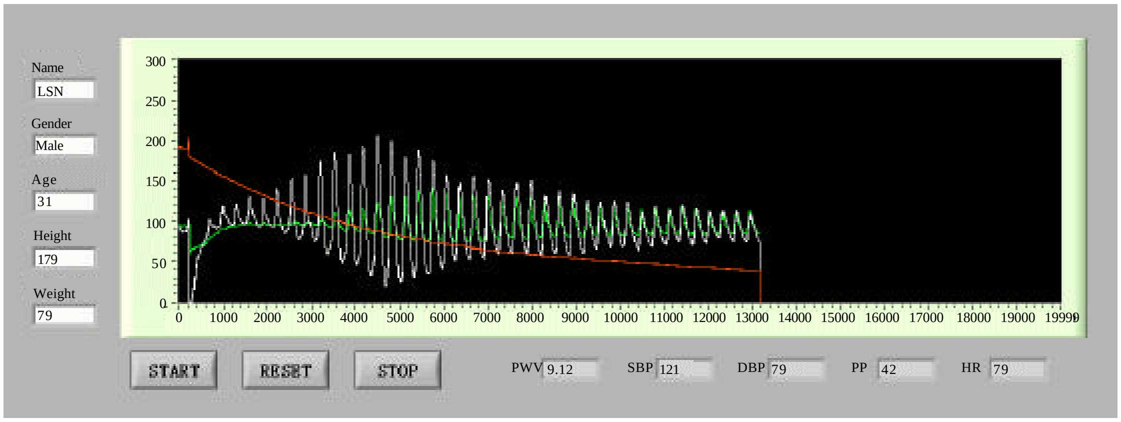


Fig. 5: Block diagram of modified algorithm of PWV


Name LSN

Gender Male

Age 31

Height 179

Weight 79

PWV 9.12

SBP 121

DBP 79

PP 42

HR 79

Fig. 6: Main interface of the device, white: Pulse wave curve of brachial artery, green: Pulse wave curve of radial artery; red: curve of cuff pressure

Software design: The PWV analysis software of the diagnostic/control module was written by the NI LabVIEW 8.6 software, a G language-based graphical programming system, which can be applied to data collection, processing, analysis and etc. The control panel of the PWV analysis software that read the pulse wave signal sent by the microcontroller through the serial interface was designed according to the serial communication parameters of the VISA serial function module. The signal was cleared of singular neighbor wave and singular peak through software programming; then a single pulse waveform to calculate PWV was filtered out through continuous wavelet transformation. The block diagram of algorithm of PWV is given in Fig. 4. Since PWV can be influenced by age, gender, blood pressure, heart rate and some other factors, it's necessary to modify the PWV measurement according to these factors, its block diagram is given in Fig. 5. The main interface of the device (Fig. 6) consisted of interfaces for patient information, control buttons, result output and

Table 1: The grouping by blood pressure levels

Grouping	Category	Case numbers	SBP (mmHg)	DBP (mmHg)
1	Normal	73	<120	<80
2	High-normal	19	120-139	80-89
3	Hypertension	31	≥140	≥90

Table 2: PWV statistics in each group

	Grouping	Mean	Standard deviation	Standard error
PWV	1	14.26	4.53	0.61
	2	17.07	6.01	1.22
	3	19.31	5.49	0.86

waveform display; users could input patient information, control the device and read the real-time waveform.

Clinical experiment: To verify the validity and reliability of the device, we carried out clinical experiment in the Dujiangyan Aeromedical Certification and Training Center of Air Force. The entire experiment was conducted in the environment where there was good ventilation and illumination and room temperature was 26°C or so. The experimental protocol passed the approval of the institutional review boards on human investigation of the university and all subjects signed a written informed consent equally. In this study, 123 volunteers without diabetes, coronary heart disease or high cholesterol were selected and divided into 3 groups according to their blood pressure, as shown in Table 1.

Each subject was required to rest for 10 min without smoking, tea, or coffee before test. During the test, the subject was in a sitting position and 2 cuffs of different sizes were tied on the left arm brachial artery and radial artery, respectively. The subject's height, age, weight and other personal information were recorded before measurement. The whole test took about 3 min and the subject was required to relax and keep quiet during this period.

RESULTS AND DISCUSSION

The result of the clinical experiment above was statistically analyzed with the SPSS 11.5 software. The averages of PWV values were compared between groups and the significance of the difference was tested by independent sample t-test ($p<0.05$ for significant difference). The statistical PWV results were shown in Table 2.

As shown in Table 2, the PWV value was significantly different between normal group and high-normal group and between normal group and hypertension group. The difference between high-normal group and hypertension group was not significant, which may be due to insufficient sample size and needs further observation. This study shows that PWV can reflect the differences between borderline hypertension and hypertension and normal blood pressure and can be used as an auxiliary for hypertension diagnosis.

PWV higher than 14 m $\sec^{-1}$ indicates a tendency of artery hardening. Of the 123 subjects, 27 were detected by our device to have PWV higher than 14 m $\sec^{-1}$. And the 27 subjects' carotid Intima-media Thickness (IMT) were further tested by Terason (2000) Doppler ultrasound diagnostic device and the results showed that 23 of them had plaque with IMT higher than 0.8 and could be judged as atherosclerosis. The conformity of the two methods was up to 85.16%, further indicating the validity of our device in atherosclerosis diagnosis by measuring PWV.

CONCLUSION

Based on the equivalent electric circuit model of artery and the principle of PWV measurement, this study proposes a noninvasive medical device for automatic measuring PWV. This device can simultaneously acquire pulse wave signals by means of cuffs which are set on the body surface of the radial artery and the brachial artery. On the basis of these signals, PWV can be calculated and used to evaluate the arterial stiffness. In order to make users conveniently operate the device, an object-oriented user interface is developed by LabVIEW. In addition, the clinical experiments show this device is considered to be effective and reliable in noninvasive diagnosis of arteriosclerosis. This research has the positive significance in relation to the prevention and early diagnosis of cardiovascular disease.

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