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APPLICATION OF THE POWER SPECTRUM ESTIMATION IN THE ANKLE-BRACHIAL INDEX DETECTION

GUOYONG WANG

Department of Mechanical Engineering, Chengde Petroleum College, Chengde 067000, Hebei, China,

E-mail: guoyong_wang@yeah.net

ABSTRACT

The key of ankle-brachial index (ABI) measurement is accurately measurement of upper and lower extremities systolic pressure. When the blood flow is blocked, blood flow will resume a normal beat and the corresponding cuff pressure of the first trough starting point is the systolic pressure. First it detects the pulse signal main frequency by spectral analysis of the pulse signal which based on the power spectrum estimation. Regarding pulse signal frequency as the basic standard, it achieves power spectrum estimation of blood flow signal with a sliding window. Last it achieves locating the position of systolic pressure by detecting whether the blood flow signal frequency and the pulse signal frequency are the same. Through simulation and experiments, it can achieve accurate detection of systolic pressure and automatic measurement of ankle-brachial index by application of this method.

Keywords: *Power Spectrum Estimation, Ankle-Brachial Index (ABI), Systolic Pressure, Spectrum Analysis, Main Frequency*

1. INTRODUCTION

With the improvement of people's living standards and the changes of diet, high-calorie and high-fat foods have been excessively intake; due to a serious shortage of physical activity, the emergence of aging, working pressure caused by social competition, excessive mental labor, acceleration of life pace and other reasons, the artery-related diseases has been rapidly increasing in the world. Arterial disease is difficult to cure. The aged-related diseases as concurrent cardiovascular and cerebrovascular diseases, hypertension, hyperlipidemia and diabetes increase the difficulty of treatment, which not only causes the high rate of illness and disability, but also seriously affect the patients' quality of life. Therefore, early detection and diagnosis of arterial disease became imminent event of medical workers[1,2]. ABI (ankle-brachial index) is an important index of diagnosing PDA (Peripheral Arterial Disease), and it is also an accurate, simple and non-invasive method of diagnosing Peripheral Arterial Ischemia. ABI is a measure to screen the PAD, and it has good correlation to various kinds of diseases such as cardiovascular disease, hypertension and renal insufficiency, which can provide very valuable information for clinicians' further judgment[3-5]. Simple, sensitive, non-invasive and high repeatable ABI detection method not only contributes to detect early atherosclerosis, but also has important guiding value of cardiovascular drugs and antihypertensive drug curative effect evaluation, the prognosis of a variety of senile systemic diseases involving vascular lesions, guiding clinical medication and the research and development of new drugs. ABI detection method has broad application prospects in the fields of basic research in clinical and experimental animals[6, 7].

ABI tests whether the detected object suffers from the lower extremity artery occlusion by calculating the ratio of the blood pressure of lower and upper extremity systolic. When the ratio is less than 0.9, it means that the lower extremity peripheral artery disease occurs[8, 9].

ABI= lower limb systolic pressure / upper limb systolic pressure

ABI is the ratio of the blood pressure of lower and upper limb systolic pressure, which is the effective basis of diagnosing and assessing the lower extremity arteriosclerosis obliterans. According to this definition, the key of ABI detection is to determine the ratio of lower and upper extremity systolic.

Since the ABI measuring technique is immature, the ABI measuring products are relatively less, and the key of ABI detection is to determine the ratio of

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lower and upper extremity systolic, the measurement of ABI is indirectly equal to measuring the ratio of lower and upper extremity systolic.

In recent years, many blood pressure monitors and automatic electronic blood pressure monitors adopt oscillametric method to measure the blood pressure indirectly. Therefore, the oscillametric method can be applied to measure the value of ABI. Due to the wide applicable scope of oscillametric method, being independent of Auscultatory method, anti-environment disturbance ability, and low pulse signal frequency, it is suitable for computer processing, and it can reliably measure the blood pressure. Oscillametric method measures the blood pressure by establishing the relations between systolic pressure, diastolic pressure, mean pressure and cuff oscillometric blood pressure [10], as shown in Figure 1. First, amplitude coefficient method depends on the characteristic coefficients basis on large samples which are collected by statistical methods. The characteristic coefficients are different to each specific individual. It is affected by pressure wave amplitude, pulse contour and arterial elasticity. In fact, the characteristic coefficients adopted by many research groups and existing products are also different. So detecting the systolic pressure and diastolic pressure by amplitude coefficient method lacks of solid theoretical foundation and it has strong experiential. The oscillametric blood pressure measurement technology which adopts the amplitude coefficient method is not accurate. Amplitude coefficient has great discreteness. Although it can make a rough judgment, it is not suitable for ABI measurement because of the requirement of accurate systolic pressure. Therefore, the value of ABI measured by oscillametric method has always been questioning.

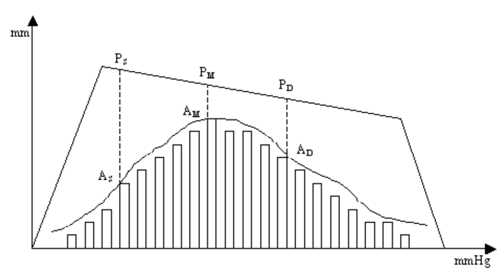

Figure 1 Oscillametric Method Measure Theory Chart

In August 2003, Korea Hanbyul Meditech Co.Ltd developed the PP-1000 atherosclerosis and vascular detection system adopting high sensitive sensor which can detect ABI. Japan Colin Company invented arteriosclerosis tester [11,12] which developed double layer Cuff by high tech, i.e. the combination of double cuff measurement and oscillametric method. Its testing method is the same as Doppler method. Set the sensing Cuff in the lower part of Cuff to test wave signals and turn the sound into the sensing Cuff signals to obtain the same accuracy as Doppler method, therefore, to measure the blood pressure of lower and upper extremity and calculate the value of ABI. The above medical instruments can detect the ABI of experimental subjects and patients, but the price is excessively expensive, only the sensor worth tens of thousands of yuan. And it needs four cuffs to measure. The accuracy of measurement has been suspected due to the incomplete same position of Cuff and sensing Cuff.

This thesis studies the theory of auscultatory method blood pressure measurement, the relation between arterial blood pressure and cuff pressure, and blood flow wave. In the thesis, a new method of measuring systolic blood pressure, i.e. the Cuff pressure which the first wave starting point of blood flow recovering wave corresponds is the systolic blood pressure. According to power spectrum estimation, detect pulse signal main frequency by the spectral analysis of pulse signal. At last, to determine the position of systolic blood pressure and achieve the automatic measurement of ABI through the detection that whether the blood flow signal main frequency is equal to pulse signal main frequency.

2. THE PRINCIPLE OF COMPUTER RECOGNITION OF SYSTOLIC PRESSURE

Using the pressure cuff of the cuff to measure the hemokinesis of the limbs artery linings, we monitor signal amplitude of the pulse fluctuations in the sensor cuff during the gradually decreasing pressure in the pressure cuff. If the amplitude of the pulse fluctuations begins to increase substantially, then the pressure in the pressure cuff is equivalent to the systolic pressure [13]. When the pressure in the compression cuff is higher than that of the upper arm, compression cuff will block the blood flow of the brachial artery through internal organization in the upper arm. While the pressure in the compression cuff decreases to the upper arm systolic pressure, blood vessel elasticity makes the blood of the brachial artery to recover flowing. The pressure in the compression cuff is the same with systolic pressure when the sensor cuff detects high amplitude pulse fluctuation. Thereby, we can obtain that the compression pressure of first trough

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starting point is the systolic pressure when the blood recover flowing. The testing principle and steps is shown in Figure 2 to Figure 5.Thus, the key is to find the position of the first trough starting point where the blood signal resumes normal pulsing. To achieve the accurate measurement of the systolic pressure, the thesis adopts sliding window methods of power spectrum estimation to detect the upper and lower extremity systolic blood pressure.

（1）In the experiment, test the natural blood flow waveform, As shown in Figure 2.

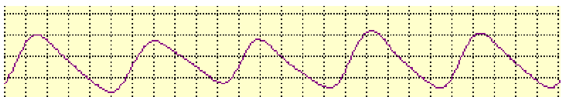

Figure 2 Waveform When Blood Flows At Natural

(2) Exert flow slowly when the cuff with sphygmomanometer binding on the arm. As shown in Figure 3, waveform fluctuates as the blood flow is influenced by the pressure of the air sac.

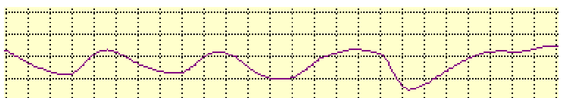

Figure 3 Waveform When Blood Is Pressed

(3) When the cuff pressure if larger than the blood flow pressure, the blood flow between the figures and the arm is nearly blocked with no flow. At this time, the blood flow waveform is almost competitive leveling straight line, as shown in Figure 4.

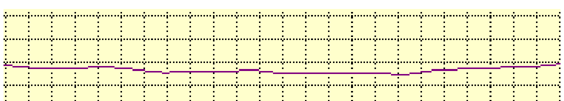

Figure 4 Waveform When Blood Is Enough Pressed

(4) Then reduce the cuff pressure slowly and continue to observe the blood flow waveform. Subsequently, the blood flow appears a jump as shown in Figure 5. The first trough starting point is corresponding to the starting point of the natural blood flow and the corresponding pressure of which is the systolic pressure of the upper limb. And the Korotkoff-Sound Method result also verifies this. Seen from the detection of the arterial blood pressure and cuff pressure by Korotkoff-Sound Method, we can get the conclusion: at the opening of arterial blood pressure, cuff pressure is equal to systolic pressure. At this point, the blood starts to pulse which is corresponding to the first Korotkoff-Sound. Thus, collecting the blood signal and the pressure signal simultaneously can confirm the systolic pressure, and then we can calculate the ABI.

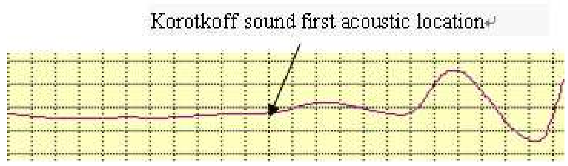

Figure 5 Waveform When Blood Flows Over Again

3. METHOD OF POWER SPECTRAL ESTIMATION

3.1 The Definition Of Power Spectral Estimation

The auto-power spectrum of random signal is also called power spectral density, which is Fu Liye transformation of its autocorrelation function[14] ,written as, $P_x(f)$ 。

$$P_x(f) = \int_{-\infty}^{\infty} R_x(\tau)\exp(-j2\pi f\tau)d\tau \tag{1}$$

Power spectrum estimation estimates the power spectrum of the signal by finite length of data. The thesis uses the classical power spectrum estimation method, the so-called direct method and is also named periodogram. It is directly obtained by Fu Liye transformation: regards the N bit sample value $x_N(n)$ as random energy signal, and then take the Fu Liye transformation which is $X_N(e^{i\omega})$, after that, take the square of the amplitude and divided by N as the real power spectrum estimation P of $X(N)$, i.e.:

$$P(\exp(j\omega)) = \frac{1}{N}|X_N(\omega)|^2 = \frac{1}{N}|X(\exp(j\omega))|^2$$

(2)

but

$$X(\exp(j\omega)) = \sum_{n=0}^{N-1} x(n)\exp(-jn\omega) \tag{3}$$

so：

$$P_x(k) = \frac{1}{N}|X(k)|^2 \quad (k = 0,1,2,\cdots,N-1) \tag{4}$$

and：

$$X(k) = \sum_{n=0}^{N-1} x(n)\exp(-j2\pi kn/N) \tag{5}$$

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3.2 Sliding Window Selection

In the actual digital signal processing, it often requires the observation time of the signal to be limited in a certain time interval and also needs to select a period of time signal be analyzed. Such interception of a limited amount of data is the signal data truncation process. This is conducive to perform spectrum analysis of the blood flow signal and will be easy to find the corresponding starting point of the systolic blood pressure, which is equivalent to add a moving "window". Accordance with normal pulse of the frequency range of the experimenter, the sample frequency, as well as the basic principle of spectrum analysis, the selected length of the sliding window is 600[15] .

3.3 Error Elimination Of Spectrum Analysis

In digital signal processing, it realizes the data spectrum analysis mainly through DFT and FFT; at the same time, according to the previously description, in order to find the corresponding starting point of the systolic blood pressure more easily , it needs to carry out sliding window data interception, which will cause analysis error. Two of the most important analytical errors are picket fence effect and spectral leakage [16].

3.3.1 Elimination of the picket fence effect

The suppression and elimination of the picket fence effect is mainly by increasing the intercepted data length. The methods of increasing the length of intercepted data are as following: (1) By increasing the number of data points N to change the length of the data interception; (2) By supplementing zero on interception data terminal to increase the data length.

Although the above two methods increase the interception length, the former way increases data sampling points which can see more spectral lines that can not been catched before lengthened. The latter lengthening is the zero value at the end of the data, which has no effect on the calculation results of the spectral analysis and it can make the spectrum become dense while maintaining the original spectral shape. In this experiment, we used the second method, a method to achieve zero-padding at the end of the data.

3.3.2 Suppress spectral leakage

The suppression of spectrum leakage is primarily through lengthening the intercepted data and changing the shape of the window. However, the lengthening of the intercepted data will greatly increase the calculated amount and is unfavorable for data analysis. From the principle point of view, to reduce a truncation error, we should magnify main lobe or minish the side lobe so that the actual spectral is approximately to the original spectrum. But from the view of perspective of energy conservation analysis: when the side lobe minishes, then the main lobes will magnify; side lobe magnifies, the main lobe will minish. The latter is likely to cause confusion of side lobe and main lobe and the misunderstanding of the two main lobes. Therefore, it is generally possible to increase the main lobe and refine side lobe, so that the energy is concentrated in the main lobe. The essence of this approach is: because the side lobe is high-frequency component, reducing side lobe is trying to decrease the high-frequency component and appropriately increase the low frequency components. Data interception is equivalent to using a rectangular window function window. As the rectangular signal changes very fiercely in the time domain, the signal waveform is straight up and down and the high-frequency component is extremely rich and decays slowly, which causes very serious spectrum leakage. Therefore, it is possible to replace it with other window functions.

3.3.3 The application window function

According to the above-description, we can inhibit spectrum leakage by window function weighting to inhibit the amplitude characteristic side lobe of the FFT equivalent filter or make the input signal cycle of limited length delayed which can minimize the discontinuity degree on the boundary. There are two requirements for designing of the window function[16]:

(1) the main lobe width of the window function spectrum should be as narrow as possible in order to obtain a steeper transition zone;

(2) the relative amplitude of the maximum side lobe should be as small as possible in order to let the energy concentrate in the main lobe to the great extent to reduce the acromion and corrugated and improve the stability of the in-band and increase the attenuation within the stop band.

However, these two requirements can not meet simultaneously. Through the analysis and comparison of the spectrum characteristic diagrams obtained by the MATLAB simulation of a variety of window functions, we can draw the following conclusion: the application of the window function can effectively inhibit the leakage of the signal spectrum and is conductive to detect the signal's frequency. The maximum side lobe of the Hamming function is 41dB lower than the main lobe and approximately 99.963% of the energy is

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concentrated in the main lobe, which effectively controls amplitude of the side lobes.

Table 1: Usual Window Trait Schedule

Window function	Approximate transition bandwidth	Sidelobe peak amplitude	Minimum stopband attenuation
rectangle window	$4\pi/N$	-13 dB	-21 dB
triangle window	$8\pi/N$	-25 dB	-25 dB
hanning window	$8\pi/N$	-31 dB	-44 dB
hamming window	$8\pi/N$	-41 dB	-53 dB
blackman window	$12\pi/N$	-57 dB	-74 dB

4. DETECTION EMULATION REALIZATION

Because the person's heart rate is constant and the frequency of the pulse is evocated by the beating of the heart, and similarly, the frequency of normal blood flow is equal to the heart rate as they are the result of the same emits. Thus, if we regard the pulse spectrum as a standard, the frequency of normal blood flow signal should be equal to the frequency of pulse signal, all of which is the test standard and basis. Below through the MATLAB software simulation example, we will show the steps of how to detect upper extremity systolic blood pressure.

(1) First of all, search and find the starting and ending point of the normal pulse beating from the start point of every group of the pulse data, then cut out the segment data between the starting and ending points of the pulse. Find out the peak of its power spectrum and its corresponding main frequency through power spectrum estimation of the segment data. As shown in Figure 6, the power spectrum main frequency of the intercepted pulse data is 0.961Hz.

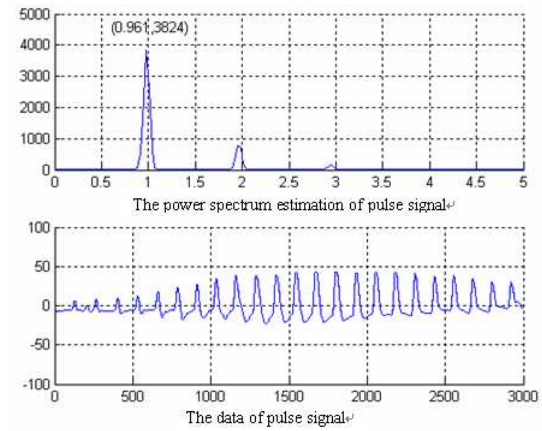

Figure 6 The Power Spectrum Estimation Of Pulse Signal

(2) From the starting point of the pulse beating, find and intercept 600 blood signal data and then carry out power spectrum estimation. According to the calculated power spectrum value, find out the spectral peaks value of the blood flow signal and its corresponding main frequency.

(3) And then check whether the main frequency of the blood flow signal and pulse signal is the same. If they are the same, it means that the starting point range of wave crest has appeared; if not, it needs to carry out power spectrum analysis of the 600 segment data successively and also inspect whether the main frequency values of the blood flow and pulse are the same until the inspection frequency value is equal. In the Figure 7, 8 and 9 the main frequency of the blood flow signal is different from that of pulse signal. As can be seen in Figure 10, the main frequency of blood flow signal and the pulse signal is the same.

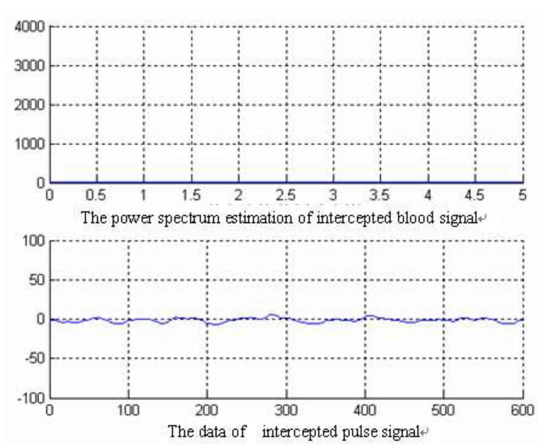

Figure 7 The Power Spectrum Estimation Of Intercepted Blood Signal

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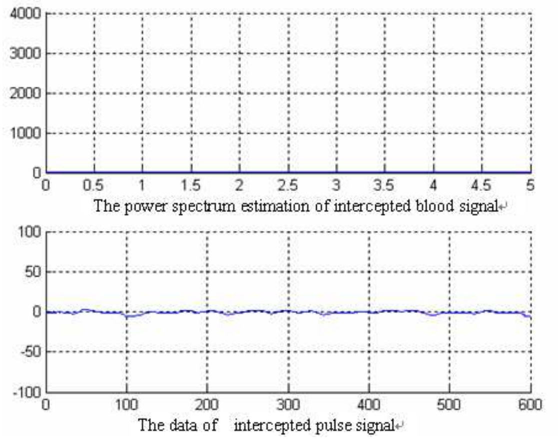

Figure 8 The Power Spectrum Estimation Of Intercepted Blood Signal

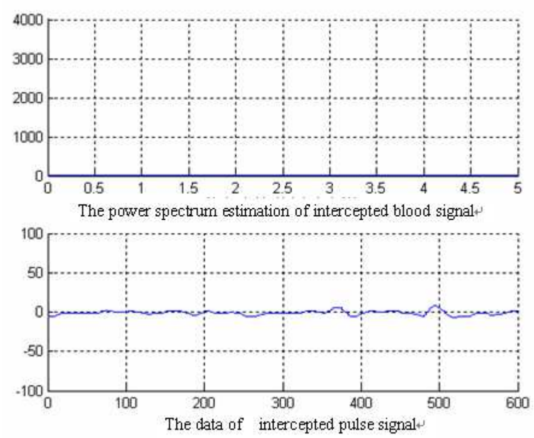

Figure 9 The Power Spectrum Estimation Of Intercepted Blood Signal

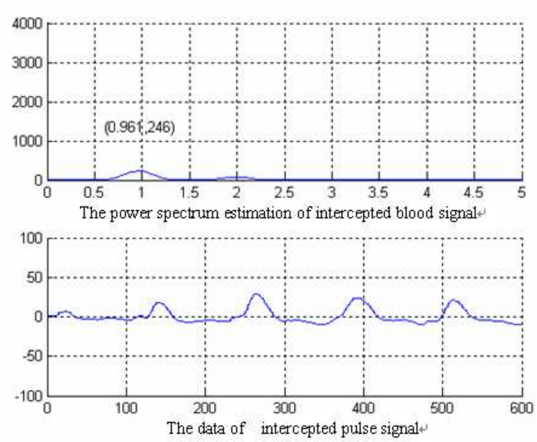

Figure 10 The Power Spectrum Estimation Of Intercepted Blood Signal

(4) When the test result shows that the main frequency of the blood flow signal and pulse signal is the same, it means that the starting point range of wave crest has appeared. Then, re-test from the last 600 data segments, namely: test the crest of following 600 data segments one by one from last data and see if the blood flow signal main frequency is the same as that of the pulse signal. If not, test the crest till they are the same, the point of which is just what we need and its corresponding pressure value is systolic pressure. In Figure 11, the main frequency of intercepted blood flow data power spectral is different with that of the pulse signal. But in Figure 12, the power spectral main frequency of the blood flow data followed the trough is the same with that of the pulse signal. Based on the blood flow signal peaks and troughs in the detection, as shown in Figure 12, the corresponding starting point of the peaks is the systolic pressure point.

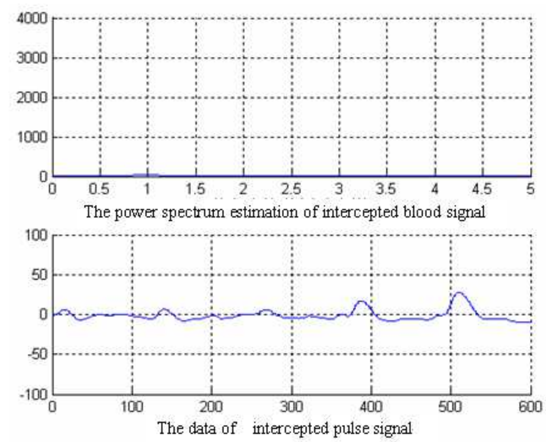

Figure 11 The Power Spectrum Estimation Of Intercepted Blood Signal

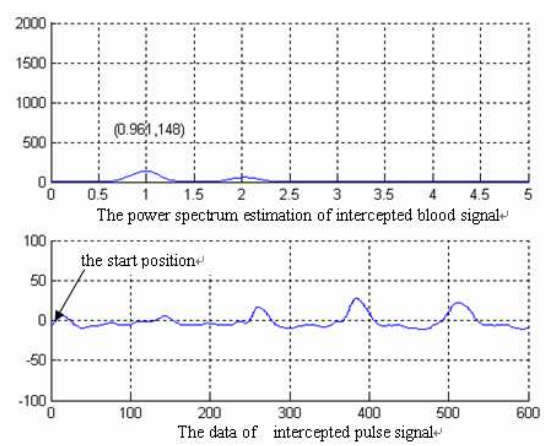

Figure 12 The Power Spectrum Estimation Of Intercepted Blood Signal

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5. EXPERIMENTAL RESULTS

Realize the power spectrum estimation through the improved Goertzel algorithm. As has been mentioned above, regarding the upper limb pulse power spectrum main frequency as the standard, the normal blood flow signal main frequency should be the same as that of the pulse signal. That's the test basis. Through the pulse signal power spectrum estimation, we can obtain the pulse signal frequency, namely the detection criteria. Then carry out the sliding window spectrum estimation and get the blood flow signal main frequency. If they are different, we need to continue the sliding window spectrum estimation till we find the same main frequency. The above method realizes the upper limb systolic pressure coarse positioning. Through the detection of the peaks and trough, it can achieve the accurate locating of upper limb systolic pressure. Comparing the experimental result with the systolic blood pressure obtained through the Korotkoff sound auscultation method, we find that they are the same, which verified the correctness of this experiment. As shown in Figure 13, the detected upper limb systolic blood pressure is 108mmHg. The detection method of the lower limb systolic pressure is the same as the upper limb systolic pressure detection.

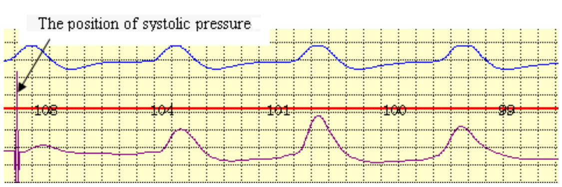

Figure 13 The Accurate Location And The Detected Realization Of The Systolic Pressure

At present, Korotkoff-Sound Method is medically recognized as the standard method of blood pressure measurement. The United States Medical Instrument Development Association (AAMI) and the British Hypertension Society (BHS) regards it as the standard and suggest the improvement of other new blood pressure measurement of methods the be compared with the Korotkoff-Sound Method . Therefor, to examine the detection accuracy of the experiment, the author applied the Korotkoff-Sound Method.

In the following 10 groups of experimental, it detects the systolic pressure of the upper and lower limb systolic and also applies the Korotkoff-Sound Method to test the blood presure as a standard. The the measurement result is recorded in Table 2. It shows that left upper limb, left lower limb, Rightupper limb, Right lower limb represent the corresponding systolic pressure; left upper Korotkoff, left lower Korotkoff, right upper Korotkoff, right lower Korotkoff represent respectively the corresponding systolic pressure results by Korotkoff-Sound Method. Left upper error, left lower error, right upper error, right lower error represents the corresponding pressure error. All units are mmHg. As can be seen from Table 2, this measurement method has high integrity and can detect the ABI of the subjects with better result.

Table 2: Experiment Result

number of times	1	2	3	4	5	6	7	8	9	10
Left upper limb	104	105	113	119	105	118	110	114	113	103
Left lower limb	100	130	134	125	99	118	114	121	122	99
Right upper limb	105	101	113	124	103	114	107	111	114	100
Right lower limb	111	146	136	153	123	139	140	131	134	124
Left upper Korotkoff	104	105	113	119	105	118	110	114	113	103
Left lower Korotkoff	101	131	132	125	102	119	118	121	124	102
Right upper Korotkoff	105	102	113	120	103	113	110	113	114	100
Right lower Korotkoff	114	144	131	150	128	136	138	131	138	121
Left upper error	0	0	0	0	0	0	0	0	0	0
Left lower error	1	1	2	0	3	1	4	0	2	3
Right upper error	0	1	0	4	0	1	4	2	0	0
Right lower error	3	2	2	3	5	3	2	0	4	3

As can be seen from the Table 2, the right lower extremity error is the maximum, right upper systolic measurement error is competitive minimum and left upper limb systolic pressure measurement is the most accurate with no error, all of which illustrates the detection accuracy of the upper limb systolic is relative higher than the lower limb

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systolic and is easier to be detected. Experimental error may have the following reasons: the subjects is uncomfortable or nervous during the detection which will cause the shaking of the upper and lower limb systolic and the shortening of the breath, as a result it will influence the measurement accuracy.

6. CONCLUSION

Using the spectrum analysis method based on power spectrum estimation and sliding window can successfully solve the problem of systolic blood pressure automatic identification and automatic detection of the ankle-brachial index. The power spectrum estimation of the upper and lower limb pulse signal and together with the regarding of the pulse signal frequency as the criteria can realize the data positioning of the blood flow signal. The adopting of sliding window spectrum analysis of the intercepted blood flow data reduces the amount of computation and achieves coarse positioning of upper and lower limbs systolic blood pressure. And then through the detection of the blood flow signal crest, it can realize the accurate locating and identification of the upper and lower limbs systolic blood pressure, which will achieve accurate detection of the ankle-brachial index.

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