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## Pulse Wave Analysis

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### 1. Introduction

Cardiovascular refers to the Cardio (heart) and vascular (blood vessels). The system has two major functional parts: central circulation system and systemic circulation system. Central circulation includes the pulmonary circulation and the heart from where the pulse wave is generated. Systemic circulation is the path that the blood goes from and to the heart. (Green 1984) Pulse wave is detected at arteries which include elastic arteries, medium muscular arteries, small arteries and arterioles. The typical muscular artery has three layers: tunica intima as inner layer, tunica media as middle layer, and tunica adventitia for the outer layer. (Kangasniemi & Opas 1997) The material properties of arteries are highly nonlinear. (langewouters et al. 1984) It depends on the contents of arterial wall: how collagen, elastin and protein are located in the arteries. Functional and structural changes in the arterial wall can be used as early marker for the hypertensive and cardiac diseases.

Blood flow is the key to monitor the cardiovascular health condition since it is generated and restrict within such system. Currently the most widely used method for haemodynamic parameters detecting is invasive thermo-dilution method. Impedance-cardiography is the most commonly used non-invasive method nowadays; however, it is too complex for clinical routine check. Pulse wave analysis is an innovative method in the market to do fast and no burden testing (Zhang et al. 2008)

Pulse is one of the most critical signals of human life. It comes directly from heart to the blood vessel system. As pulse transmitted, reflections will occur at different level of blood vessels. Other conditions such as resistance of blood flow, elastic of vessel wall, and blood viscosity have clear influence on pulse. Pathological changes affect pulse in different ways: the strength, reflection, and frequency. So pulse provides abundant and reliable information about cardiovascular system.

Pulse can be recorded to a set of time series data and represented as a diagraph which is called pulse waveform or pulse wave for short.

Gathering pulse at wrist by finger has been a major diagnosis method in China since 500 BC. Physicians used palpation of the pulse as a diagnostic tool during the examination. In 300AD, "Maijing" categoried pulse into 24 types and became the first systematic literature about the pulse. Grecian started to notice the rhythm, strength, and velocity at 400BC. Struthius described a method to watch the pulse wave by putting a leaf on the artery, which is considered as early stage of pulse wave monitoring. In 1860, Etienne Jules Mary invented a level based sphygmograph to measure the pulse rate. It is the first device can actually record the pulse wave. Frederick observed normal radial pressure wave and the carotid

wave to find the normal waveform and the differences between those waveforms. (Mahomed 1872) He figured out the special effect on the radial waveform caused by the high blood pressure. It helps to learn the natural history of essential hypertension. (Mahomed 1877) The effects of arterial degeneration by aging on the pulse wave were also shown on his work. (Mahomed 1874) His researches have been used in the life insurance field. (Postel\_Vinay 1996)

The analysis was based on the basic mathematic algorithms in nineteenth century: dividing the wave into increasing part and decreasing part, calculating the height and area of the wave. Calculus, hemodynamic, biomathematics and pattern recognition techniques has been used in pulse wave analysis by taking advantage of Information Technology. However, utilizing the classic pulse theory with current techniques is still a big challenge.

## 2. Pulse wave analysis methods

### 2.1 Research data source

With informed consent, 517 sets of testing data were collected from 318 subjects. The ages of subjects range from 1 to 91 years (mean  $\pm$  SD,  $55 \pm 20$ ). 87 subjects were chosen from normal people (mean  $\pm$  SD,  $51 \pm 17$ ) and the rest were recorded from patients in Department of Cardiology at Shandong Provincial Hospital in China (mean  $\pm$  SD,  $62 \pm 13$ ). Normal people were assigned to the control group corresponding to the patients group. All medical records were collected in order to do research on each risk factor. Risk factor groups, including smoking group (mean  $\pm$  SD,  $66.089 \pm 13.112$ ) and diabetes group (mean  $\pm$  SD,  $64 \pm 11.941$ ), are created based on the risk factors from medical records.

### 2.2 Pulse wave factors

Using pulse data directly is unreliable since any change of haemodynamic condition has effects on pulse wave data. But there are still many researches for pulse wave analysis because the pulse data is much easier and safer to get than most other signals. With considering related conditions, pulse wave factors analysis can achieve higher accuracy.

Most recent researches give positive results with comparing pulse wave factors analysis and standard methods. Pathophysiological Laboratory Netherlands did study on continuous cardiac output monitoring with pulse contour during cardiac surgery (Jansen 1990). Cardiac output was measured 8 to 12 times during the operation with pulse contour and thermodilution. The result shows linear regression between two methods. The cardiac output calculated by pulse wave factors is accurate even when heart rate, blood pressure, and total peripheral resistance change.

To reduce the effects of other factors, pulse wave factors had been tested among different groups. Rodig picked two groups of patients based on ejection fraction: 13 patients in group 1 with ejection fraction greater than 45% and 13 patients in group 2 with ejection fraction less than 45%. Both pulse wave factors and thermodilution technique had been used to calculate the cardiac output 12 times during the surgery. The mean differences for CO did not differ in either group (Rodig 1999). The differences became significant when systemic vascular resistance increased by 60% and early period after operation. It suggested that pulse wave factors analysis is a comparable method during the surgery. Calibration of the device will help to achieve more accurate result.

The patients with weak pulse waveform or arrhythmia should always avoid using the result of pulse wave factors as the major source since it become unreliable in such environment.

Early Detection of cardiovascular diseases is one of the most important usages for pulse wave monitoring. The convenience noninvasive technique makes it extremely suitable for widely use at community levels. Factors derived from pulse wave analysis have been used to detect hypertension, coronary artery diseases. For example, losing the diastolic component is the result of reduced compliance of arteries. (Cohn 1995) Pulse wave is suggested to be early marker for those diseases and guide for health care professions during the therapy.

Pulse wave were used to be analyzed in two ways: point based analysis, area based analysis. Point based analysis is usually designed for specific risk factor. It picks up top, bottom points from different components of the waveform or derivative curve. Then the calculation is done regarding to the medical significant of those points. Stiffness Index is a well-known factor in this category.

Arteries stiffen is a consequence of age and atherosclerosis. Two of the leading causes of death in the developed world in nowadays, myocardial infarction and stroke, are a direct consequence of atherosclerosis. Arterial stiffness is an indicator of increased cardiovascular disease risk. Among many new methods applied to detect arterial stiffness, pulse wave monitoring is a rapidly developing one.

Arterial pulse is one of the most fundamental life signals in medicine, which has been used since ancient time. With the help of new information technology, pulse wave analysis has been utilized to detect many aspects of heart diseases especially the ones involving arterial stiffness.

Total arterial compliance and increased central Pulse Wave Velocity (PWV) are associated with arterial wall stiffening. They are recognized as the dominant risk factors for cardiovascular disease. The contour of the peripheral pressure and volume pulse affected by the vascular aging on the upper limb is also well-known. The worsen artery stiffness with an increase in pulse wave velocity is cited as the main reason for the change of pulse contour.

PWV is the velocity of the pulse pressure. The blood has speed of several meters per second at the aorta and slow down to several mm per second at peripheral network. The PWV is much faster than that. Normal PWV has the range from 5 meters per second to 15 meters per second. (O'Rourke & Mancia 1999)

Since pulse pressure and pulse wave velocity are closely linked to cardiovascular morbidity, some non-invasive methods to assess arterial stiffness based on pulse wave analysis have been introduced. However, these methods need to measure the difference of centre artery pulse and the reflected pulse wave, which is a complicated process. On the other hand, the Digital Volume Pulse (DVP) may be obtained simply by measuring the blood volume of finger, which becomes a potentially attractive waveform to analyze.

Millasseau et al have demonstrated that arterial stiffness, as measured by peripheral pulse wave analysis, is correlated with the measurement of central aortic stiffness and PWV between carotid and femoral artery, which is considered as a reliable method in assessment of cardiovascular pathologic changes for adults. They introduced the Stiffness Index (SI), which was derived from the pulse wave analysis for artery stiffness assessment and was

correlated with PWV ( $r=0.65$ ,  $P<0.0001$ ). It is an effective non-invasive method for assessing artery stiffness.

Pulse Wave Velocity is the golden standard for arterial stiffness diagnosis. Researches show that Stiffness Index has equivalent output as PWV. It uses the reflection of the pulse as the second source to get the time difference without additional sensors which make it more applicable to the Home Monitoring System. As shown in figure 1, the systolic top shows the time that pulse reach the finger; diastolic top represents the time that pulse reflection reach the finger. The distance that pulse goes through has direct relationship with the height of the subject. SI can be calculated by  $h/\Delta t$ .

Area Based analysis specialized in the blood volume monitoring such as Cardiac Output (CO). The attempt for getting cardiac output from pulse wave started more than one hundred years ago (Erlanger 1904). The pulse wave is the result of interaction between stroke volume and arteries resistance. Building the model of arterial tree helped the calculation of CO from pulse wave. The simplest model used in clinic contains single resistance. Other elements should be involved in the calculation including capacitance element, resistance element (Cholley 1995).

Not all models have reliable results, even some widely used one can only work in specific environment. Windkessel Model consists of four elements: left ventricle, aortic valve, arterial vascular compartment, and peripheral flow pathway. Testing of the model in normotensive and hypertensive subjects shows that the model is only valid when the pressure wave speed is high enough with no reflection sites exist (Timothy 2002).

Cardiac Index (CI) is an important parameter related to the CO and body surface area. Tomas compared the CI value among pulmonary artery thermodilution, arterial thermodilution and pulse wave analysis for critically ill patients. The mean differences among three methods are within 1.01% and standard derivation are within 6.51%. (Felbinger 2004) The pulse wave factors provide clinically acceptable accuracy.

In addition to long term monitoring, pulse wave analysis is also useful for emergency environment. Cardiac Function can be evaluated within several seconds.

### 2.1.1 Stiffness Index

The pulse wave sensor detects the blood flow at the index finger and tracks the strength of the flow as pulse wave data. To record the pulse wave, the patients were comfortably rested with the right hand supported. A pulse wave sensor was applied to the index finger of right hand. Only the appropriate and stable contour of the pulse wave was recorded.

As shown in Figure, the first part of the waveform (systolic component) is result of pressure transmissions along a direct path from the aortic root to the wrist. The second part (diastolic component) is caused by the pressure transmitted from the ventricle along the aorta to the lower body. The time interval between the diastolic component and the systolic component depends upon the PWV of the pressure waves within the aorta and large arteries which is related to artery stiffness. The SI is an estimate of the PWV about artery stiffness and is obtained from subject height ( $h$ ) divided by the time between the systolic and diastolic peaks of the pulse wave contour. The height of the diastolic component of the pulse wave relates to the amount of pressure wave reflection.

SI is highly related to the pulse rate because it is calculated by the time interval between systole and diastole. Younger people with high pulse rate can get a relative high score than older people with slow pulse rate. Adjustment based on pulse rate can be applied on SI calculation.

The testing results based on age are shown in Figure and Figure, which indicate that the adjusted SI is more sensitive than SI.

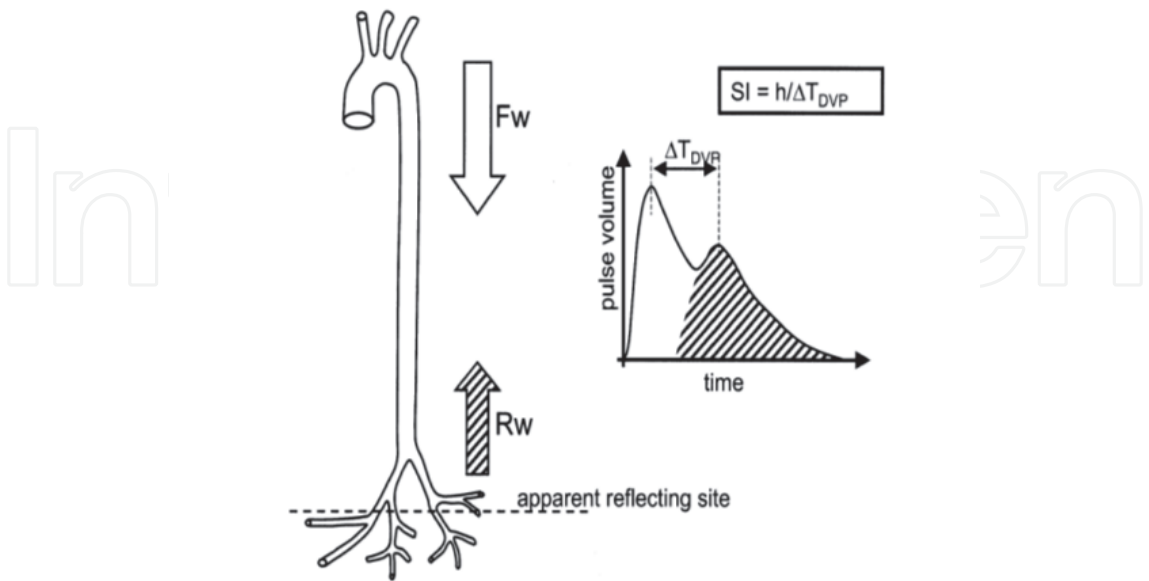


Fig. 1. Stiffness index is related to the time delay between the systolic and diastolic components of the waveform and the subject’s height

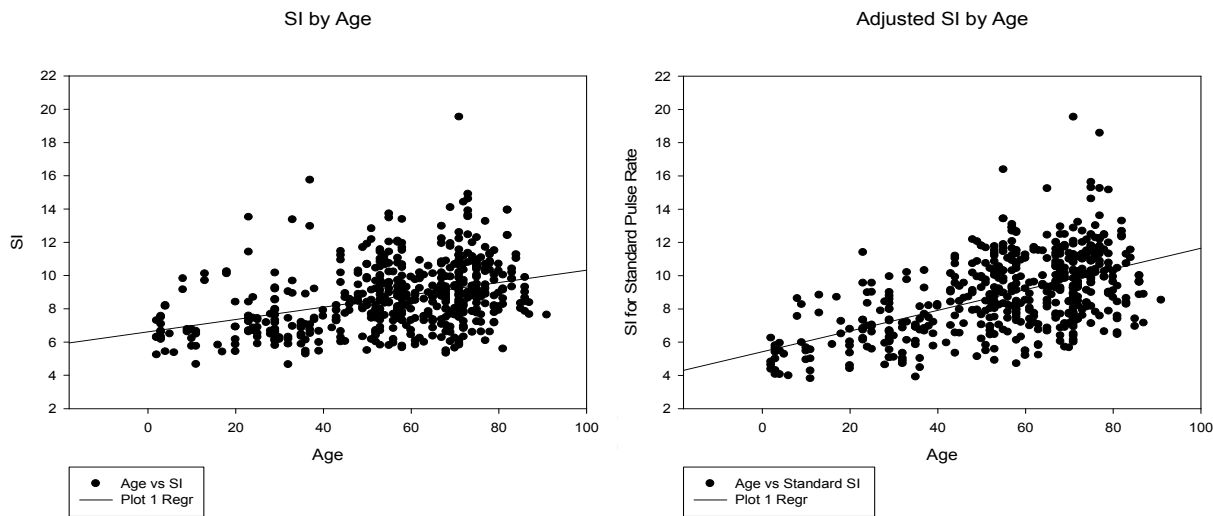


Fig. 2. Correlation for Stiffness Index and age ( $r=0.275$ ,  $p = 9.833E-019$ ). A closer relationship could be found between adjusted Stiffness Index and age. ( $r=0.536$ ,  $p=7.279E-040$ )

In order to test the sensitivity of primary factor SI, we compare it with the collected data from different groups. SI is much higher in patients group (SI:  $9.576 \pm 2.250$ ) than that of control group (SI:  $7.558 \pm 1.751$ ). On the other hand, it has positive correlation with age for both groups. All people in patients group came from the Department of Cardiology at Shandong Provincial Hospital and most of them have atherosclerosis which is the main reason for arterial stiffness. This result shows that the SI is a significant factor in pulse wave analysis to detect the degree of arterial stiffness.



Risk factor groups are very important in this research. Diabetes group (SI:  $9.975 \pm 2.174$ ) and smoking group (SI:  $10.039 \pm 2.587$ ) have even higher SI than patients group as a whole. SI is reliable for research to detect risk factors.

By analyzing with different factors, SI is found to be correlated with age, weight, and systolic blood pressure. With the comparison of patients and control groups, we find that SI has less correlation with age for patients with heart disease. However, when people have other risk factors such as smoking and diabetes, SI has no longer visible correlation with age. It also indicates that SI is sensitive to cardiovascular diseases and risk factors. People who have cardiovascular diseases or risk factor will have higher than normal SI. In general, illness and risk factors will have more impact on SI. This makes SI a perceptible indication in diagnosing arterial stiffness.

SI can be affected by the cardiac condition as we described before. The adjusted SI can only rectify influence of heart rate in a certain level. Other abnormal cardiac conditions, such as heart failure, will disturb the pulse wave form in different ways. A basic judgment of cardiac condition will make SI more catholicity.

### 2.1.2 Cardiac Output

The pulse contour method for calculation of cardiac output can be done based on the theory of elastic cavity (Liu & Li, 1987).

- Blood flow continuous equation:

$$\begin{aligned} Q_{in} &= Q_{out} + \frac{dV}{dt_1} \\ Q_{out} + \frac{dV}{dt_2} &= 0 \end{aligned} \quad (1)$$

where  $Q_{in}$  is the volume of blood flowing into the artery and  $Q_{out}$  is the volume of blood flowing into the vein.  $t_1$  and  $t_2$  are the systolic and diastolic period, respectively.

- Equation between pressure remainder and blood flow:

$$Q_{out} = \frac{p - p_v}{R} \quad (2)$$

where  $p$  is the arterial pressure,  $p_v$  is the venous pressure, and  $R$  indicates the peripheral resistance of cardiovascular system.

- Arterial pressure volume equation:

$$AC = \frac{dV}{dp} \quad (3)$$

where AC is a constant that depends on the arterial compliance.

Based on the above three equations, the analytic equation of elastic cavity can be calculated:

$$\begin{aligned} Q_{in} &= AC \frac{dp}{dt_1} + \frac{p - p_v}{R} \\ AC \frac{dp}{dt_2} + \frac{p - p_v}{R} &= 0 \end{aligned} \quad (4)$$

Computing the integral of Equation (4):

$$\begin{aligned}
 S_v &= AC(p_s^* - p_d) + \frac{A_s}{R} \\
 AC(p_d - p_s^*) + \frac{A_d}{R} &= 0
 \end{aligned}
 \tag{5}$$

where  $S_v$  is the stroke volume during a heartbeat. We refer to Figure 4 for  $A_s$ ,  $A_d$ ,  $p_s$ , and  $p_d$ . Cardiac Output is highly correlated to age, weight, and systolic blood pressure. It shows the working status of the heart while SI shows the degree of arterial stiffness. We can also find that many subjects in patients group have abnormal Cardiac Output ( $CO: 4.567 \pm 1.309$ ). But there is no significant correlation between SI and CO. Therefore, CO is a good complement of SI for analyzing cardiovascular condition.

### 2.3 Waveform analysis

The calculation based on the points with special meanings is very sensitive in the detection of risks. It uses simple algorithm to achieve the balance of performance and accuracy. But it's difficult to evaluate the overall cardiovascular condition only with several risk factors. The pulse is produced by the cooperation of heart, blood vessel, micro circulation and other parties. The more information included the more accurate classification we can get. This research used some sample wave forms to represent the different categories. A wave form belongs to a category if it's more similar to the wave form in that category than any other wave forms.

#### STUDY DATA

11 Aug 2000, 8:46:18 AM Height, Weight (BMI) 175cm, 64kg (20.9 kg/m<sup>2</sup>) Operator ID:  
Medication: irbesartan natrilix  
Notes:

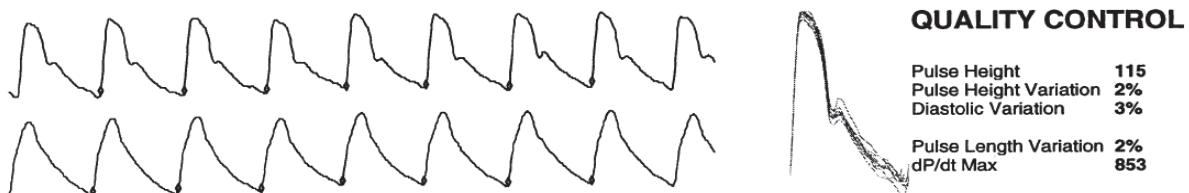


Fig. 3. Variation for continue waveforms. (O'Rourke 2001)

Pulse wave is relatively stable under the testing condition: subject setting in a quite environment and keeping calm. The pulse wave analysis result is highly repeatable in this condition. Actually the similarity of pulse waveforms doesn't change a lot under similar cardiovascular health condition even the heart rate and pulse strength changed, so waveform analysis can fit in different scenarios other than specific testing environment.

There are several classification system for the pulse wave. In the paper "Characteristics of the dicrotic notch of the arterial pulse wave in coronary heart disease", Tomas treat the notch as the indicator and classify pulse wave into four categories as following:

- Class I: A distinct incisura is inscribed on the downward slop of the pulse wave
- Class II: No incisura develops but the line of descent becomes horizontal
- Class III: No notch is present but a well-defined change in the angle of descent is observed
- Class IV: No evidence of a notch is seen



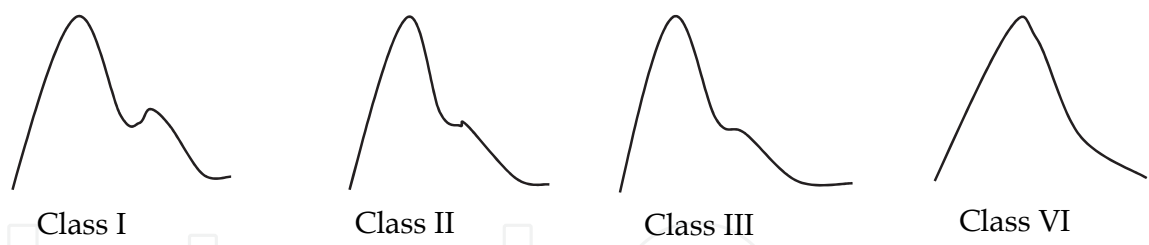


Fig. 4. Four classes of waveform based on dicrotic notch

This classification focus on the notch of the wave form which is considered as the indicator of arterial stiffness. Bates evaluates continues wave forms to include other possible diseases. He gave detail description of the pulse wave and discussed the cause of each pulse wave type. Possible diseases were also provided in his research.

| Pulse type       | Physiological cause  | Possible disease   |
|------------------|--|--|
| small & weak     | decreased stroke volume  | heart failure, hypovolemia, severe aortic stenosis   |
|                  | increased peripheral resistance                                    |  |
| large & bounding | increased stroke volume  | fever, anaemia, hyperthyroidism, aortic regurgitation, bradycardia, heart block, atherosclerosis |
|                  | decreased peripheral resistance                                    |  |
|                  | decreased compliance   |  |
| bisferiens       | increased arterial pulse with double systolic peak                 | aortic regurgitation, aortic stenosis and regurgitation, hypertropic cardiomyopathy              |
| pulsus alternans | pulse amplitude varies from peak to peak, rhythm basically regular | left ventricular failure   |

Table 1. Possible diseases which can be diagnosed based on the different types of cardiovascular pulse shapes (Bates 1995).

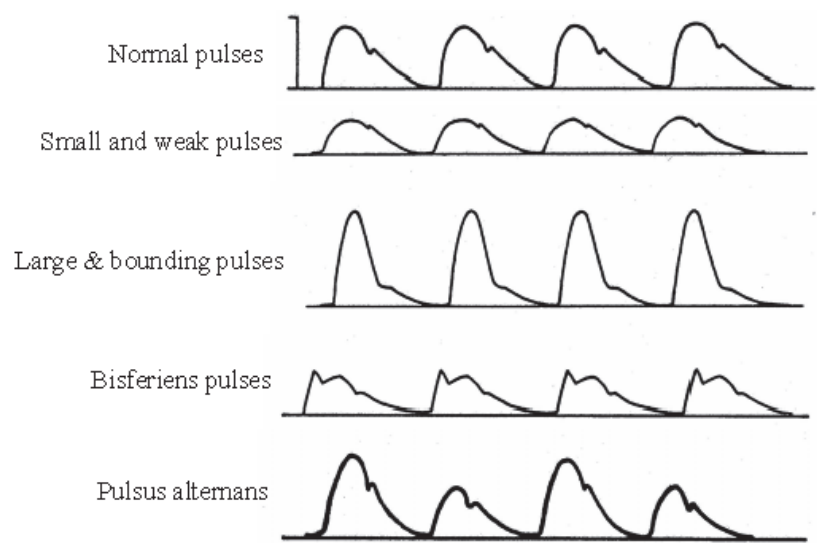


Fig. 5. Pulse wave classification from Bates

In order to get more precise information from the wave form, researchers take the traditional pulse diagnosis as the reference and mapping the characters of pulse diagnosis with the pattern of wave form. It can be used to detect certain cardiovascular risk as well as the classification. For example, acute anterior myocardial infarction will have a sharp systolic component and very small diastolic component which suggests poor blood supply.

2.2.1 Fourier transform and wavelet

Fourier Transform and Wavelet Transform have been used to perform the basic analysis on the pulse waveform. Fourier transform is a basic and important transform for linear analysis which usually transfers the signal from time domain (signal based on time) to frequency domain (the transform depends on frequency).

The Fourier theory states that any continuous signals or time serial data can be expressed as overlay of sine waves with different frequencies. This process can help signal analysis because the sine wave is well understood and treated as simple function in both mathematics and physics. Fourier transform calculates the frequency, amplitude, and phase based on this theory. Significant features could be detected by Fourier transform from similar time series data with big differences in frequency domain.

The Fourier transform can be treated as a special calculus formula that expresses the qualified function into sine basis functions. The function with the lowest frequency is called the fundamental. It has the same repetition rate of the periodic signal under evaluation. The frequency of other functions is integer times of the fundamental frequency.

Inverse Fourier transform can be used to recover the time series signal after the analysis on frequency domain is done.

With comparing the original waveform and transform data, some special features can be detected in the frequency domain.

The regular waveform from a normal subject has data nearly U shape distributed in the frequency domain. Lower frequencies and higher frequencies get bigger values and the slop goes smoothly from negative to positive. The peak value at lower frequency side is almost 50% bigger than the peak value at higher frequency side. The data become inconspicuous for frequencies between10 and 190 Hz. The higher values in time domain will result in the higher value in frequency domain.

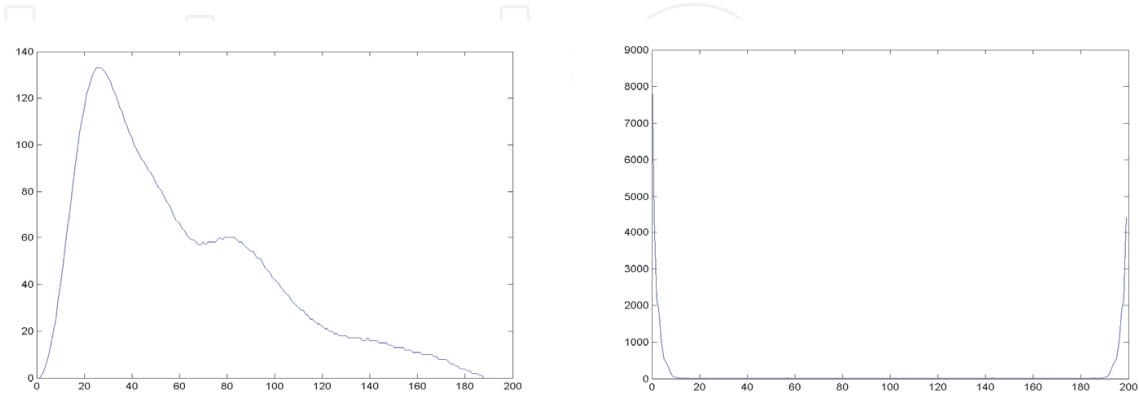


Fig. 6. Fourier Transform for a typical pulse waveform

Patients with old myocardial infarction often have obtuse systolic component and weak diastolic component due to the abnormal cardiac function. The diastolic component has a

round top and much wider than the normal waveform. This feature will generate a local maximum value at around 7Hz and 193Hz. This feature can be used to detect the cardiac function diseases which cause slow change rate at pulse waveform.

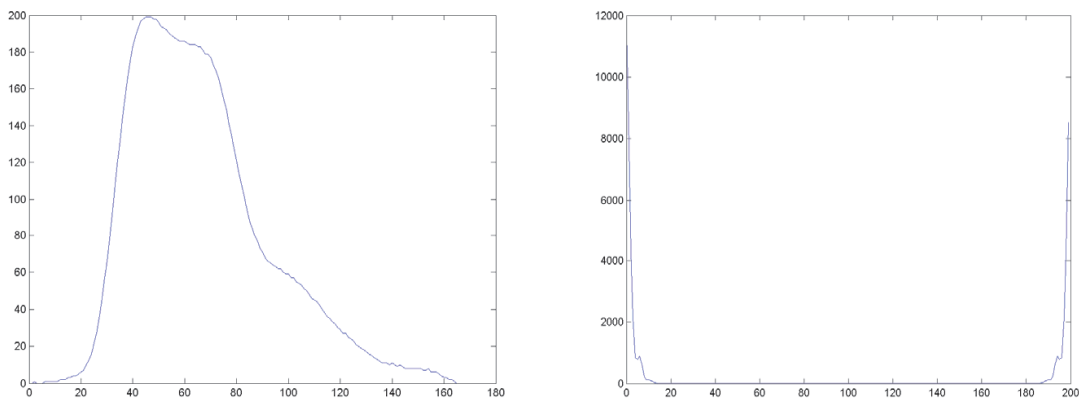


Fig. 7. Typical waveform of old myocardial infarction and their Fourier Transform

In a group of 100 selected testing data (50 normal waveform and 50 typical waveforms for old myocardial infarction), 48 testing data has local maximum at around 7Hz and 52 has smooth U shape distribution at frequency domain. 6 normal waveforms have been classified to old myocardia infarction by mistake and 8 typical myocardia infarction waveforms were not detected. Some possible reasons for mistake in the test:

- 1. Big wide diastolic component may cause the local maximum value in frequency domain.
- 2. Slow heart rate
- 3. Unstable pulse
- 4. Incomplete waveforms caused by device

The shape of diastolic component is important to arterial stiffness analysis. But it's difficult to get the corresponding features at frequency domain because the diastolic part is relatively small and can be easily affected by systolic part in FFT. The features for arterial stiffness can not be derived directly from the Fourier transform.

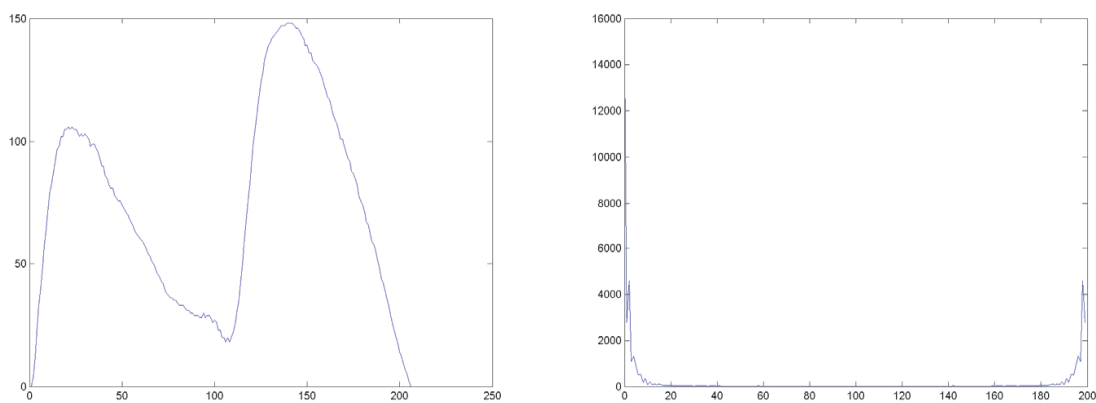


Fig. 8. Arrhythmia cause the second pulse arrives in advanced while the first pulse waveform is not complete yet. FFT shows that multi local maximum values appear at both higher frequency end and lower frequency end.

Arrhythmia is a common abnormal electrical activity in cardiovascular system. The heart rate might go too fast or too slow which will cause the waveforms change shape among continuous pulses. This feature can be captured in both time domain and frequency domain. The basic feature in time domain is time variance among continuous pulses exceeding the average level. The incomplete waveforms and merged waveforms often result in the pulse detection fails which is also a sign of arrhythmia. Eight typical arrhythmia waveforms have been identified from testing data and the patients do have arrhythmia history on file.

Features from FFT are helpful to detect some disease or certain cardiac condition, but it's difficult to achieve high accuracy by frequency domain analysis only.

Wavelet transform is well known for localized variations of power analysis. It uses the time and frequency domains together to describe the variability. Wavelet functions are localized in space while Fourier sine and cosine functions are not.

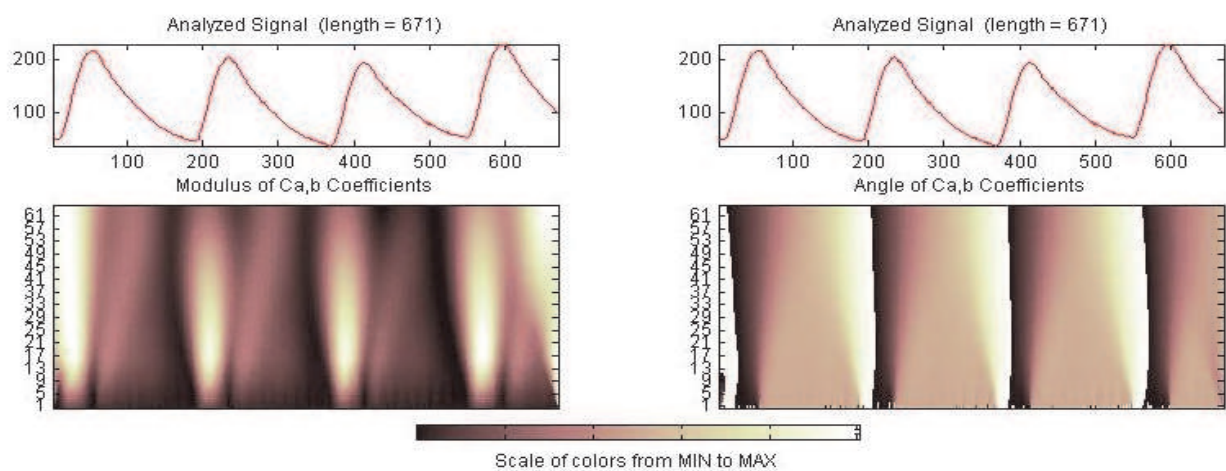


Fig. 9. Wavelet transform for pulse wave with no diastolic component.

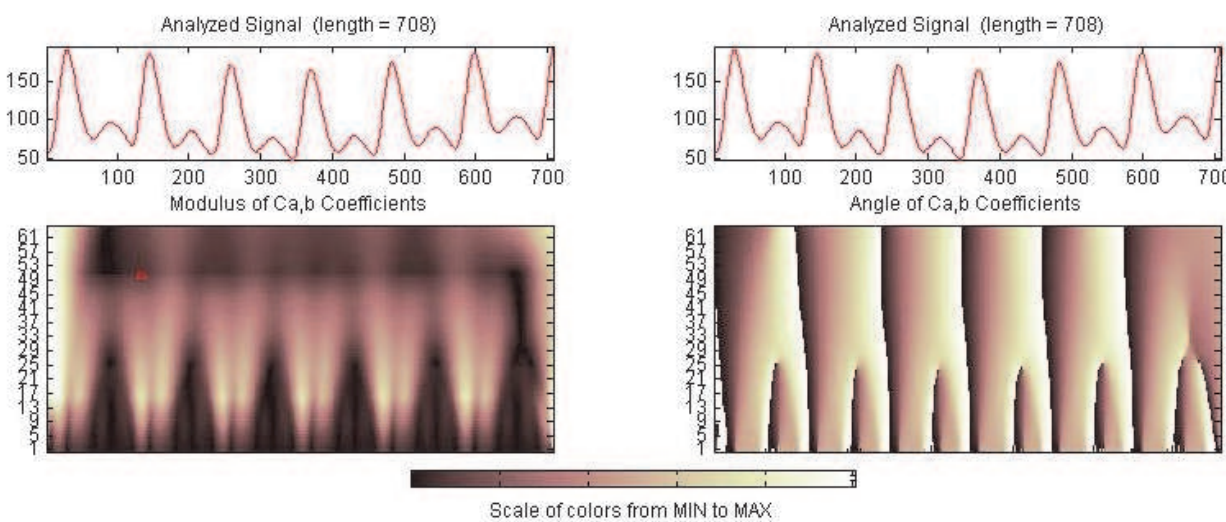


Fig. 10. Wavelet transform for pulse wave with clear diastolic component.

The algorithm can extract information from many kinds of data including audio and images especially in geophysics fields. It has been used to analyze tropical convection (Weng 1994),

the El Niño–Southern Oscillation (Gu 1995), atmospheric cold fronts (Gamage 1993), central England temperature (Baliunas 1997), the dispersion of ocean waves (Meyers 1993), wave growth and breaking (Liu 1994), and coherent structures in turbulent flows (Farge 1992). Wavelet provides multi-resolution analysis to the source data that make the result more adequate for feature detection.

Fig. 9. and Fig. 10 show the difference between pulse wave with diastolic component and pulse wave without diastolic component. Diastolic component can be easily detected by value variance among adjacent points. It has significant impact on slope changes of continuous values. It also generates additional peak values at Wavelet transform result.

### 2.2.2 Waveform similarity

Since pulse data is two dimensional time serial data, the mining techniques for time serial data can be applied on it. The waveforms can be categorized based on the similarity between testing waveform and well classified sample waveforms. Because the waveforms have same structure: taller systolic component with lower diastolic component following, the similarity calculation can achieve high accuracy. It can be measured by the total distance of corresponding points between sample waveform and testing waveform warping.

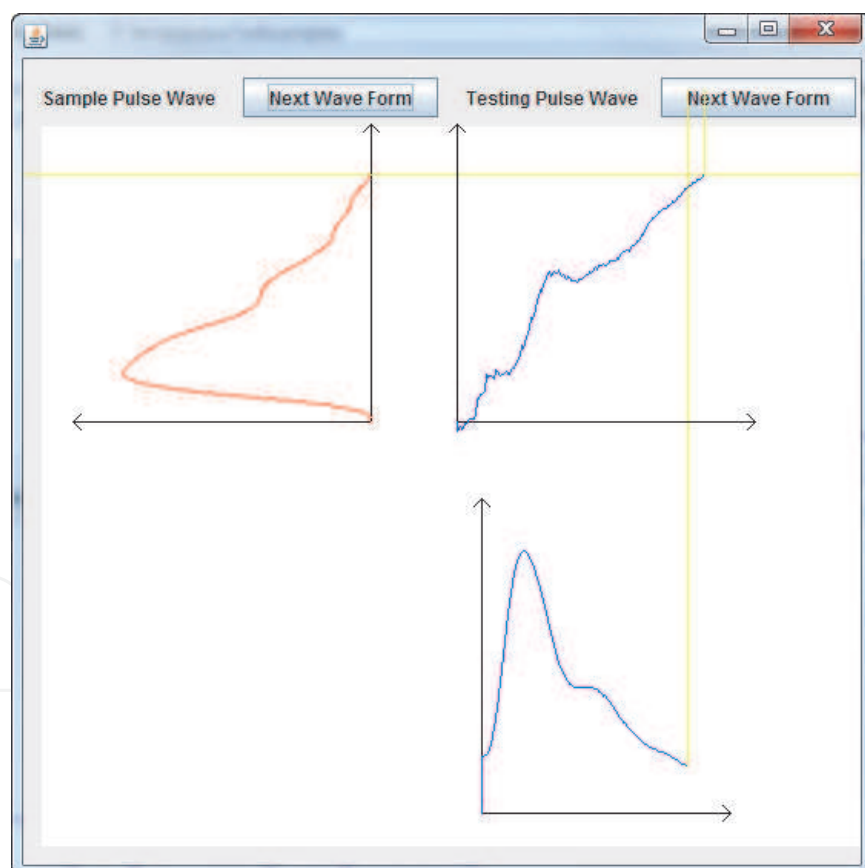


Fig. 11. Demonstration for waveform difference comparison

One of the most fundamental concepts in the nonlinear pattern recognition is that of 'time-warping' a reference to an input pattern so as to register the two patterns in time. The DTW proposed by Sakoe and Chiba (1971) is one of the most versatile algorithms in speech recognition. Figure shows the basic idea about the time warping.



The majority application for DTW was speak recognition in the early research period. (Sakoe 1978) It achieve higher recognition rate with lower cost than most other algorithms. Medical data has been analyzed with DTW recently. ECG is one of the most common signals in health care environment, so most researches focus on ECG signal analysis.

DTW was applied to ECG segmentation first since segmenting the ECG automatically is the foundation for abnormal conduction detection and all analysis tasks. DTW based single lead method achieve smaller mean error with higher standard deviation than two-lead Laguna's method. (Vullings 1998)

DTW

A sample waveform is denoted as  $\{x_i(j), 1 \leq j \leq J\}$ , and an unknown frame of the signal as  $\{x(i), 1 \leq i \leq I\}$ . The purpose of the time warping is to provide a mapping between the time indices  $i$  and  $j$  such that a time registration between the waveforms is obtained. We denote the mapping by a sequence of points  $c = (i, j)$ , between  $i$  and  $j$  as (Sakoe and Chiba 1978)

$$M = \{c(k), 1 \leq k \leq K\} \quad (6)$$

where  $c(k) = (i(k), j(k))$  and  $\{x(i), 1 \leq i \leq I\}$  is testing data,  $\{x_t(j), 1 \leq j \leq J\}$  is the template data. Warping function finds the minimal distance between two sets of data:

$$d(c(k)) = d(i(k), j(k)) = \|x(i(k)) - x_t(j(k))\|_2 \quad (7)$$

The smaller the value of  $d$ , the higher the similarity between  $x(i)$  and  $x_t(j)$

The optimal path minimize the accumulated distance  $D_T$

$$D_T = \min_{\{M\}} \sum_{k=1}^K d(c(k))w(k) \quad (8)$$

Where  $w(k)$  is a non-negative weighting coefficient.

To find the optimal path, we use

$$D(c(k)) = d(c(k)) + \min (D(c(k-1))) \quad (9)$$

Where  $D(c(k))$  represents the minimal accumulated distance

There's two restrictions for warping pulse wave

1. Monotonic Condition:  $i(k-1) \leq i(k)$  and  $j(k-1) \leq j(k)$
2. Continuity condition :  $i(k) - i(k-1) \leq 1$  and  $j(k) - j(k-1) \leq 1$

The symmetric DW equation with slope of 1 is

$$D(c(k)) = d(c(k)) + \min \begin{pmatrix} D(i(k-1), j(k-2)) + 2d(i(k), j(k-1)) \\ D(i(k-1), j(k-1)) + 2d(c(k)) \\ D(i(k-2), j(k-1)) + 2d(i(k-1), j(k)) \end{pmatrix} \quad (10)$$

The optimal accumulated distance is normalized by  $(I+J)$  for symmetric form.

To implement this algorithm, I designed three classes: TimeSeriesPoint, TimeSeries, and DTW. TimeSeriesPoint can hold an array of double values which means the algorithm can process signals from multiple sensors or leads. The number of signals is defined as the dimensions of the time series data. The get function will return the value for a specific signal based on the input dimension. There are also some utility methods to return the data array, hash the value, or check the equivalence to other TimeSeriesPoint.



TimeSeries is a collection of TimeSeriesPoints. A list of labels and a list of time reading are provided for the time series data to mark the time and special points. Label and time reading can be retrieved for each point by the method `getLabel(int n)` and `getTimeAtNthPoint(int n)`. The size of the TimeSeries is the number of TimeSeriesPoints stored in the data structure. Method `getMeasurement(int pointIndex, int valueIndex)` is provided to find the value of specific signal at the given time point.

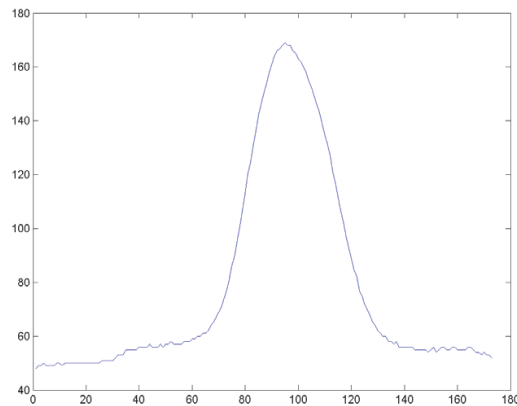


Fig. 12. Pulse wave form from a patient with acute anterior myocardial infarction

The above pulse wave was taken from a male patient at department of cardiology. He had a history of myocardial infarction for 8 years and came to the clinic again for angina pectoris. His cardiac function was rated as NYHA level IV and had to sleep in bed.

The waveform is a typical one with poor cardiac function. The systolic part is very sharp and narrow that suggests very low Cardiac Output. The diastolic component is lost since the weak pulse. Blood vessel condition is not measurable because the cardiac function is in an accurate stage.

The characteristics of this pulse wave can be summarized as following:

- Low pulse pressure
- Low cardiac output
- At least half of the waveform is around the base line
- Sharp and narrow systolic component
- No diastolic component

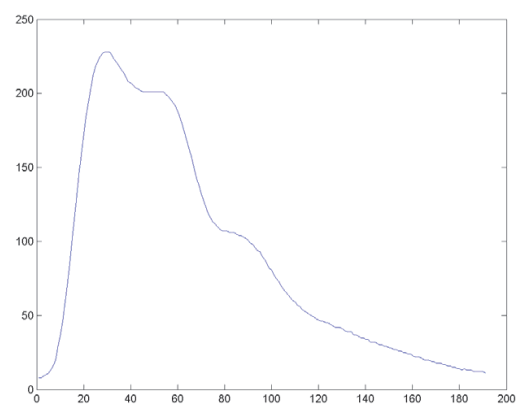


Fig. 1. Pulse wave for patient with Old myocardial infarction and degenerative valvular disease

The above pulse wave is collected from a patient with old myocardial infarction and degenerative valvular disease. He has chest distress and ictal thoracalgia for eighteen years. Gasping happened for the recent 6 months and the pain increased in intensity for the last 3 months. The patient also has mitral regurgitation and tricuspid regurgitation that make him difficult to finish some daily activities. His cardiac function is rated NYHA IV.

The waveform has regular shape with diastolic component. The systolic part becomes broader than usual which might because of the compensatory blood supply after myocardial infarction. The waveform has multiple peak values after systolic top should be the result of old myocardial infarction and degenerative valvular disease.

With review of similar waveforms and medical history, waveforms in this category have

- The waveforms have a broader systolic component
- The diastolic component could have different shape depends on the arteries condition.
- The cardiac output usually has normal values.

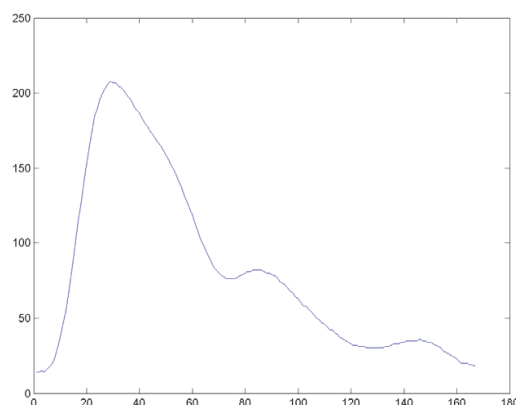


Fig. 2. Pulse wave for a patient with Ventricular aneurysm

This pulse wave belongs to a 57 years old male patient. Coronary angiography shows that arteriostenosis at left anterior descending artery reduce 40% - 50% of the artery's capacity. The first diagonal branch and leftcircumflex also have arteriostenosis. Ventricular aneurysm occupies 30% chambers of the heart.

The systolic part of waveform doesn't have very clear features. The diastolic component goes vertical direction longer than normal waveform. A little uplift could be observed at the end of diastolic component.

There are eight patients with Ventricular aneurysm in the pulse database and 6 of them have pulse wave belong to this category.

- Major significance in diastolic part, give more weight when calculating distance
- Having extra step to check the end of diastolic component will help to identify the waveform

A fifteen years old male patient took the pulse wave test after admission in hospital. He had palpitation for eight years and had oliguresis, edema of lower extremity for recent 3 months. He had fast heart rate which could reach 140/min. The heart border expanded to left and the pulse was weak. Cardiac ultrasonic shows that left ventricle had spherical expansion. The interventricular septum and ventricular wall were thin. The cardiac output and cardiac index decreased.

This class of waveform is characterized by separated systolic component and diastolic component. The pulse pressure decreased to a very low level before the diastolic component and the diastolic part is relatively bigger.

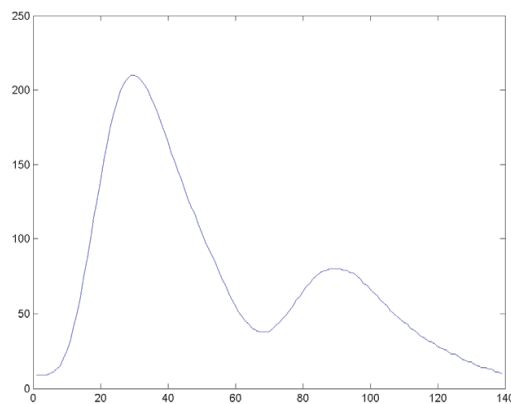


Fig. 3. Pulse wave for Dilated cardiomyopathy

### 3. Pulse wave monitoring system

Analysis techniques have strength on different areas. Pulse wave factors have good detection rate for cardiovascular risks. Waveform analysis is more suitable for over all evaluation and cardiovascular health classification. The combination of both strategies is the model proposed in this thesis.

The monitoring system is designed to adapt this model. Single test data can provide some hints of subject's health condition. If showing the history data of the subject together, the trend line of the health condition is much more valuable for subject's treatment. Considering the similar pulse data with medical records gives additional support for decision making.

The system includes four modules to handle the data acquisition, transfer and local storage. The four modules are (Figure): Electrocardiogram Sensor, Pulse Oximeter Sensor, Non Invasive Blood Pressure Sensor, a computer or mobile device collecting vital signs and transmitted to Control Center.

Since patients have various risk at different time periods, whole day model will be established during the training period. Usually some measurements are significantly lower at night such as systolic blood pressure, diastolic blood pressure, pulse rate etc. The system will create different criteria for risk detection based on training data. This solution gives continuous improvements at server side for both individual health condition analysis and overall research on pulse wave.

Control Center accepts two types of data: real time monitoring data and offline monitoring data. Real time monitoring aims at detecting serious heart condition in a timely manner. Real time data are bytes (value ranged from 0 – 255) transferred in binary format in order to reduce bandwidth consuming. The standard sampling rate is 200 points per second and can be reduced to 100 or 50 points per second based on the performance of the computer or portable device. Once the connection is initialized, device will send data every second which means up to 200 bytes per channel. The maximum capacity of real time data package

contains 3-lead ECG and 1 pulse wave data. A modern server can easily handle more than one hundred connections with high quality service at the same time.

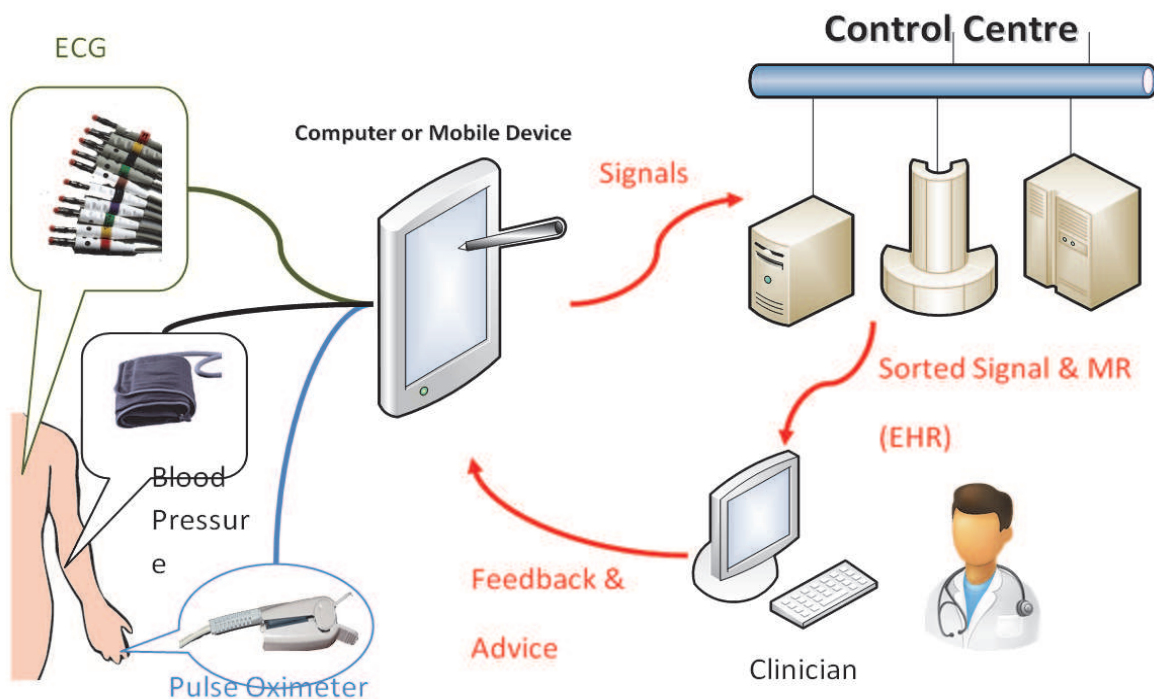


Fig. 4. Remote Monitoring System using pulse oximeter, ECG, and Blood pressure

Control Center has Distributed Structure to improve the Quality of Service. The Gateway is responsible for load balance and server management. It accepts connection requests and forwards them to different servers. Local server will receive high priority for the connections which means servers are likely to serve local users first. Those servers which can work individually, will process the messages in detail. We can easily maintain servers in the system and problem with one server will not affect the system in this way. Servers will select typical and abnormal monitoring data with the statistic logs (monitoring time, maximum, minimum, average of monitoring values, etc) and upload back to data center for future references. Data center has ability to trace the usage of specific user based on the routing records.

The abnormal ECG or Pulse Wave forms will be detected at server side. Actions might be taken after the data is reviewed by medical professionals. Control center will contact the relatives or emergency department in some predefined situations.

Offline data will be generated at client side regarding to the usage. It also includes the typical and abnormal monitoring data with the statistic logs. The system provides a web based application for user to manage monitoring records. Users can easily find out their health condition among specific time period with the help of system assessment. Doctors' advice may add to the system when review is done.

Research verifies that the medical data is more valuable if they can be analyzed together. Data transfer and present layers follows the Electronic Health Record standard. The monitoring network not only backup data, analyze them in different scales, but also provide the pulse data on the cloud to convenience users accessing their pulse records anytime from home, clinic and other places.

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