ANALYSIS OF RADIAL ARTERIAL PULSE WAVEFORM

A dissertation

submitted in partial fulfillment of the requirements

for the degree of

Master of Technology

by

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Abstract

The radial arterial pulse signal can provide valuable diagnosis information about cardiovascular health. This project involved spectral analysis of pulse wave and the changes of area under the curve because of exercise. The cross correlation between some of physiological signals such as radial arterial pulse (RAP), pulse plethysmogram (PPG) and ECG has been studied for the purpose of delay calculation between them. The variation in delays due to exercise has also been studied, as a possible indicator of cardiovascular health.

Contents

List of symbols

Symbol	Explanation
F_l	Hold-down force
P_a	Foot of pulse
P_b	First shoulder
P_c	Second Shoulder
P_d	Incisura

List of abbreviations

Symbol	Explanation
ECG	Electrocardiogram
PCG	Phonocardiogram
RAP	Radial arterial pulse
PPG	Photoplethysmogram
MAP	Mean arterial pressure
MSP	Mean systolic pressure
MDP	Mean diastolic pressure
Sa/s	Samples/second
SER	Spectral energy ratio
PSG	Pulse spectral graph
FFT	Fast fourier transform
BP	Blood pressure
HR	Heart rate
bpm	Beats per minute
HD	Harmonic distortion
SMF	Spectral mean frequency
SDF	Standard deviation frequency
NSK	Normalized skewness

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Chapter 1
INTRODUCTION

1.1 Overview

Radial arterial pulse contains very important information about the body condition, vascular condition and heart functions. The pulse is generated at aorta after the contraction of ventricle and then passes to arterial tree. Noninvasive measurement of pulse waveform from radial artery can be very valuable. The temporal characteristics and spectral characteristics of pulse are very important for diagnosis purpose. The cross correlation of pulse wave with other physiological related waveforms is very useful for vascular disorder diagnosis. In western medicine, 'taking the pulse' is a part of battery of diagnostic procedures, and is often used only for heart rate and variability. While for the physicians practicing *ayurveda,* traditional Tibetian medicine, Unani medicine, and traditional Chinese medicine, etc, a study of a patient's pulse is of paramount importance [1].

1.2 Objective

This project is in continuation of analysis done earlier at IIT Bombay as the part of M.Tech. project by Sarika Gattawar [2]. Her project included acquisition of various physiological signals along with RAP, the spectral analysis of RAP signal before and after various state of exercise, and the cross correlation analysis of pulse signal with other physiological signals like PCG (phonocardiogram), ECG (electrocardiogram), PPG (photoplethysmogram).

The objective of this project is to extend the work done by Sarika Gattawar [2]. Recording of the pulse waveform using blood flow profiler is done for purpose of calculation of pulse wave velocity more accurately. The recording has been done at two different sites along the same artery simultaneously. Various methods to calculate delay are verified such as peak-to-peak, foot-to-foot and cross correlation. The variation of area under the pulse wave after exercise is also studied. The relationship of heart rate with

RAP-ECG delay is studied at rest condition and after exercise. The spectral analysis of pulse signal obtained by velocity profiler is also carried out.

1.3 Dissertation outline

In the second chapter of the report, pulse wave reflection theory along with different pulse sensing techniques is discussed. Chapter 3 describes the analysis of the pulse waveform done by various researchers around the world. Chapter 3 also includes a description of experimental set up used for signal acquisition by Sarika Gattawar [2] and analysis techniques used to investigate the effect of physical exercise on the pulse waveform. The results and discussion are presented in Chapter 4. The last chapter gives summary of the work carried out and scope for future work.

Chapter 2

PULSE WAVE ACQUISITIION

The arterial pulse wave is a combination of incident and reflected waves in arterial tree. The impedance discontinuity causes the primary pulse wave reflections from the bifurcations and vascular beds. If the aorta was an open ended tube then there would have no wave reflection and therefore no difference between the pressure wave and the flow wave would occur. The impedance to the flow through the great vessels is almost constant, while the impedance increases significantly at level of arterioles. This contributes significantly to pulse reflection. The pulse wave is shown in Fig.2.1 along with the reflected wave (dotted line curve) and resultant wave [3].

Vasoconstrictions produce only slight increase in amplitude because the peripheral resistance is already high. On the other end vasodilation reduces the amplitude and delays the return of the reflected wave.

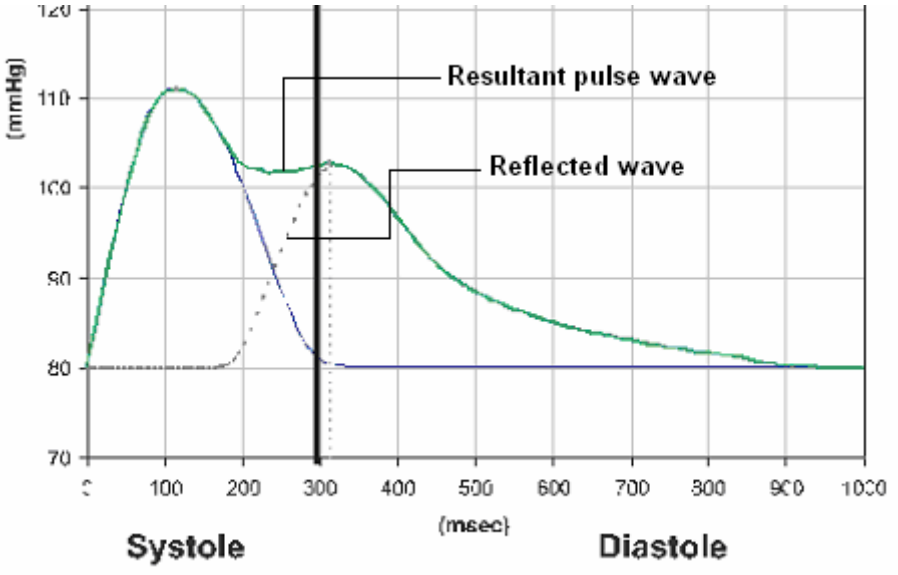


Fig 2.1 Aortic pulse wave [3]

Pulse can be considered as generated due to pressure gradient along the arterial tree or due the change of volume, or due to flow velocity profile change. Several techniques for acquisition and analysis of radial arterial pulse have been reported. Some of these are described here.

2.1 Dudgeon's sphygmograph

Dudgeon has designed the arterial pressure measuring device in 1882. It is known as Dudgeon's sphygmograph. This device is used to measure blood pressure from radial artery at the wrist position as show in Fig. 2.2 [5]. The pressure pulse at wrist causes the metal strip to move a stylus on smoked paper and pressure variation data is recorded on the smoke paper as shown in figure 2.2. Upadhyay [6] had used the Dudgeon's sphygmograph to obtain pulse tracing for quantitative measurement of three pulses (*vata, pitta, kapha*) classified in accordance with *nadishastra.*

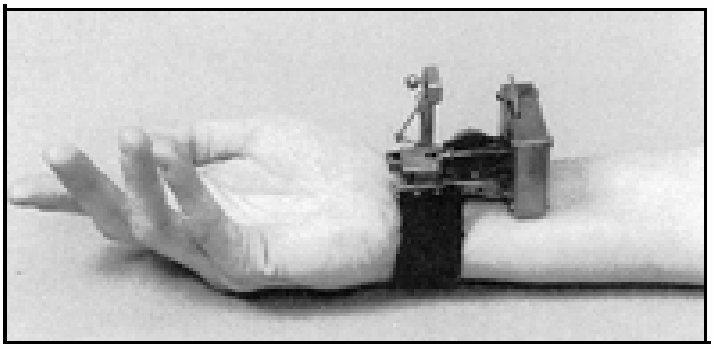


Fig 2.2 Dudgeon's sphygmograph [5]

2.2 Arterial tonometer

Arterial tonometry is the process to measure the force (pressure) being exerted by the blood vessel and transmitted through the skin to the sensor. Typically it is placed over the superficial artery, radial artery on the wrist [7]. It is continuous blood pressure measurement throughout the heart cycle and not only the systolic and diastolic pressure values. Pulse pressures has emerged as a better predictor of cardiac ischemic events compared to systolic, diastolic, and mean brachial pressure [8].

Fig 2.3 shows simplified model of tonometer. P represents the blood pressure in superficial artery and F is the force measured by a tonometer transducer. The forces and moments are acting on the frictionless piston. The membrane is assumed to transmit only tensile force T, and does not transmit bending moment. The tension vector (T) is perpendicular to the pressure vector (P). The measured force (F) is independent of T, and

depends only on the blood pressure and the area (A) of the frictionless piston. Thus, the measured force (F) represents the intra-arterial pressure [7].

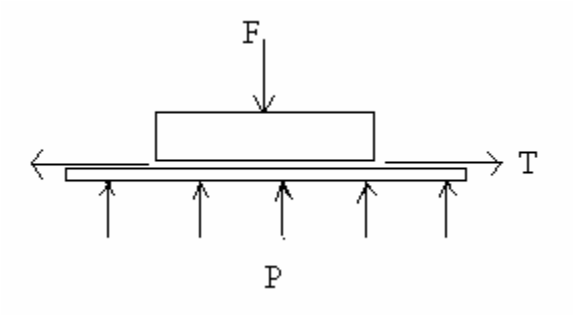


Fig 2.3 Idealized model for a tonometer [7]

The basic requirements for the measurement are,

- The artery must be supported by a bone below the artery.
- The skin thickness over the artery should be insignificant compared to artery diameter.
- The sensor should be smaller than the flattened area of the artery.

The device consists of a sensor placed on the wrist over the radial artery. This sensor contains piezoelectric pressure transducers separated by ~0.2 mm as shown in Fig 2.4. A pneumatic pump and bellows press the transducer array against the skin and tissue above the artery. This pressure is known as the hold down pressure (HDP). When the artery is partially flattened, a graph, called a tonogram, can be plotted to show sensor pulse amplitude versus transducer number as shown in Fig 2.5. The individual sensor elements whose pulse amplitudes are near the maximum pulse amplitude are calibrated to the systolic and diastolic values obtained in the oscillometric cuff measurement [8].

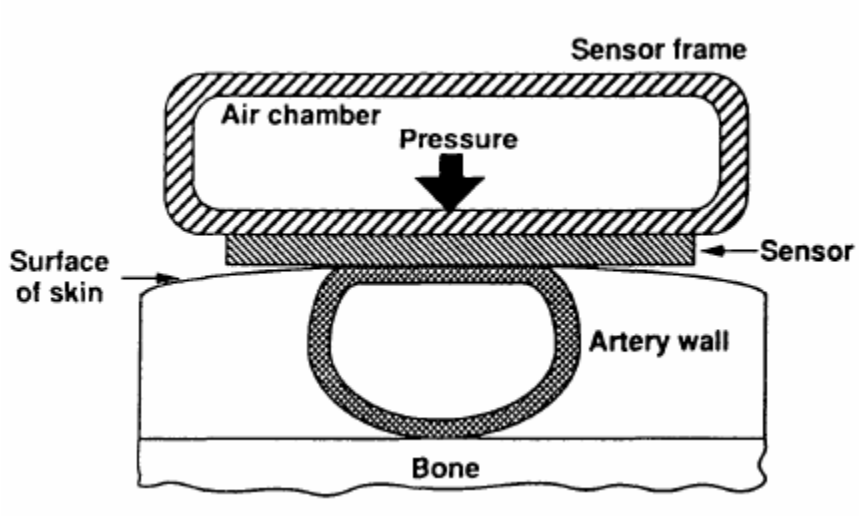


Fig 2.4 Sensor used in tonometer [8]

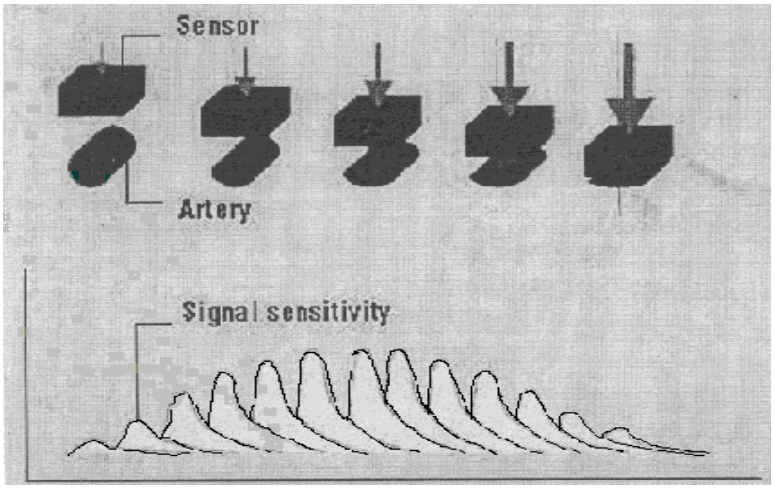


Fig 2.5 Procedure for obtaining optimal hold-down pressure [8]

Some of the limitations of arterial tonometry

(1) If the sensors are to be placed over a curved portion of the artery, an artifact would be added to the blood pressure signal. The voltage level of the artifact would vary over the course of the cardiac cycle because the arterial wall expands and contracts during a cycle as the blood flows through it.

Solution: Use sensors as small as possible so that its surface will not extend beyond the confines of the flattened portion of the artery.

(2) Tonometers typically suffer from motion artifact, which is a kind of noise that is added to the signal of interest, in this case the blood pressure.

Solution: Reference transducer be contained within the tonometer housing but positioned such that it is not over the palpable artery. Then, a subtraction of the resulting reference signal from the signal obtained from the artery would reduce or even completely remove the motion artifact. If the common mode noise picked up by both sensors were exactly equal, then there would be complete removal of the artifact as a result of the subtraction.

2.3 Photoplethysmography

Plethysmography is the determination of blood flow in a limb by measurement of volume changes of the limb. The plethysmograph produces a waveform similar to the arterial pulse pressure wave, but to date it is not possible to calibrate plethysmograph wave in terms of pressure units [9]. The plethysmograph waveform is useful to study pulse velocity and indicating the arterial obstructions.

Photoplethysmography is based on the determination of the optical properties of a selected skin area. The plethysmograph probe consists of light source (photodiode) and photo detector (phototransistor). Infra-red radiation from the emitter diode passes into the skin and is reflected, scattered and absorbed by dermal tissue, by vascular tissue, and by blood. As the dilatation wave passes the probe, the volume of blood in its vicinity increases and the amplitude of detected signal falls. A change in reflection will cause a change in voltage drop across the photo sensor. Consequently, the backscattered light corresponds with the variation of the blood volume. Blood volume changes can then be determined by measuring the reflected light and using the optical properties of tissue and blood [10].

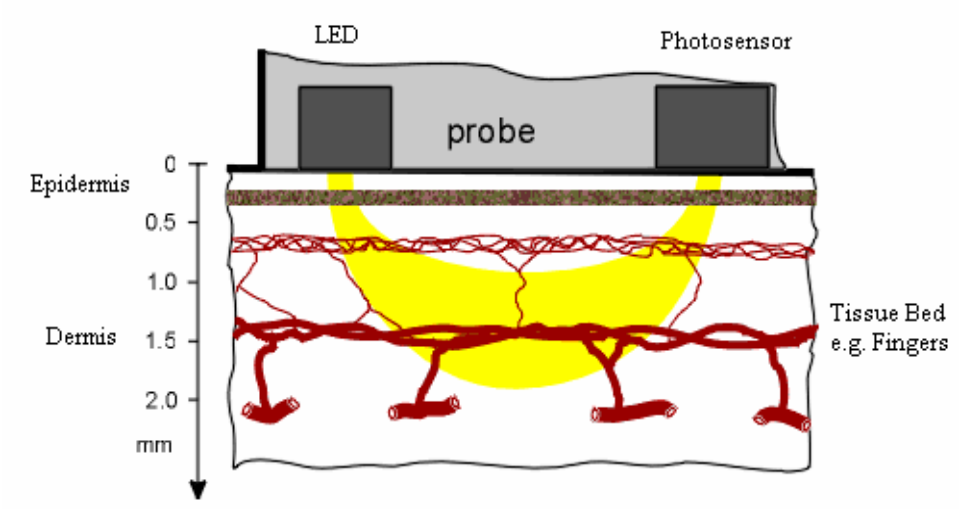


Fig 2.6 Photoplethysmography in reflection mode [10]

The application of photoplethysmography

- Diagnosing arterial diseases in fingers and toes just by watching the curve shape.
- Diagnosing functional disturbances of blood flow
- In case of the thoractic outlet syndrome the arteries in the shoulder is occluded by some extensions of the shoulder, the arms or the head. By monitoring the pulse wave in a digit, the positions where the shoulder arteries are occluded may be found.
- Especially with transmission probes it is very easy to measure the peripheral systolic blood pressure. The PPG-probes are used as blood flow sensors (instead of the widespread but much more difficult to use doppler probes). A cuff is inflated to aoversystolic pressure and than deflated slowly. The systolic blood pressure is the cuff pressure where the PPG-probe just measured a pulse wave again. With small cuffs even a blood pressure measurement on digits is possible.

Ugnell's study [11] shows, frequency spectra analysis of the PPG signals can provide valuable information on heart function, respiration, vascular condition and nervous system. This PPG does not provide calibrated volume changes. Its usefulness is limited to pulse velocity measurement, pulse oximeter applications and heart rate measurement.

2.4 Doppler based blood flow velocity profiler

The blood flow through the vessel is not constant throughout the cross section of the vessel but it is function of the distance from wall surface. The velocity is nearly zero near the vessel wall and it is highest at the centre of the vessel. If the local blood velocity exceed certain limit, small eddies can occur and laminar flow changes into turbulent for which the flow rate is more difficult to determine [12].

The main advantages are

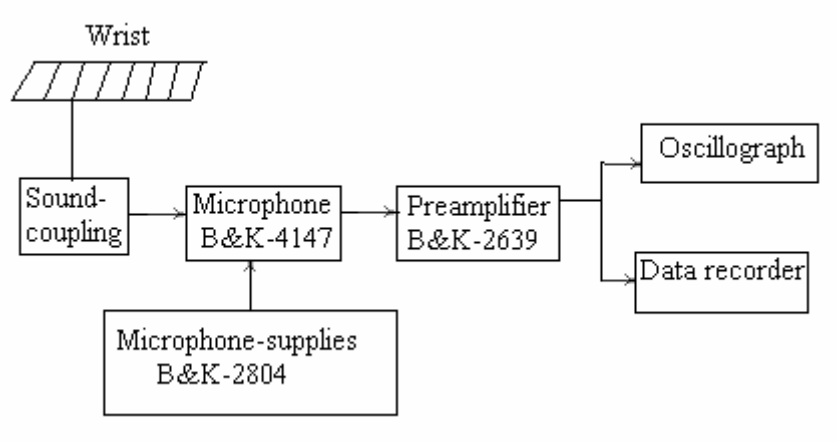
- By selecting particular frequency a particular artery can be selected.
- It can be used with infants and hypotensive individuals.
- It can be done in high noise environment.
- This principle can be used in early detection of arteriosclerosis or atherosclerosis by measuring blood flow / determining elasticity of artery.

The disadvantages of technique are

- Motion artifacts might cause the change in ultrasonic path between transmitter and receiver.
- Air between the transducer and object might cause the reflection of sound directly.

2.5 Microphone based system

The microphone based system is reported by Binghe and Jinglin [13] in 1998. This system is used to record the pulse from radial artery. The block diagram of the system is shown in Fig 2.7. The main components are sound-coupling cavity, condenser microphone (B&K- 4147), preamplifier (B&K- 2639), microphone power supply (B&K-2804).



2.7 Microphone based pulse sensing system for pulse signal [13]

The microphone is used as transducer to convert pulse in electrical signals. This electrical signal is then preamplified for further processing.

2.6 Pulse acquisition done at IIT Bombay

Surve [14] has recorded the pulse signal using electronic stethoscope or phonocardiograph. These sensors are generally used for recording of heart sound and murmurs produced in heart valve. The PCG and pulse waveform were acquired by using two different devices, named “Medetron” and “Stethmate”. Both are made of air-coupled piezoelectric crystal.

The recording was limited by the diameter (1.5”) of chest piece microphone. It is larger compare to the radial artery diameter. Hence along with the pulse signal, the external environment noise and signal from other vibrating vessel were added. So this type of recording can only be used for timing relationship (delay) with other physiological related waveforms. The other problem was the poor low frequency response of the crystal.

Further, piezoelectric transducer used was 0.5” diameter, which is less compared to the chest piece microphone. The transducer was kept in place over radial artery by closing the velcro strap firmly around the wrist. Position was adjusted in order to get the optimal signal strength. The obtained pulse waveform was much less noisy as compared to that from the phonocardiograph sensor. Fig. 2.8 shows the pulse waveform recorded using phonocardiograph sensor and piezoelectric transducer.

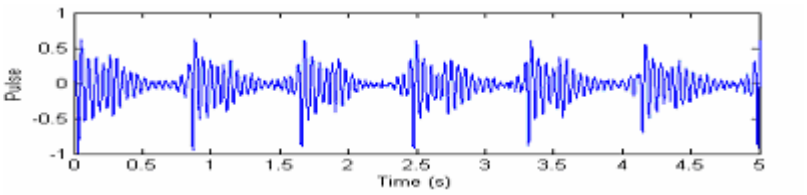


Fig 2.8 (a) Pulse acquisition using phonocardiograph sensor [14]

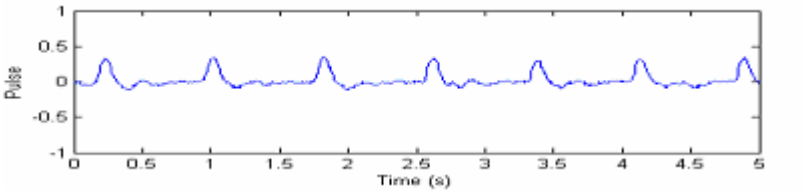


Fig 2.8 (b) Pulse acquisition using piezoelectric transducer [14]

Gattawar [2] had recorded radial arterial pulse (RAP) waveform along with other physiological signals like finger photoplethysmogram (PPG), phonocardiogram (PCG) and ECG for five days of five subjects. On each subject, recording was done under full rest condition, and then the subject exercised on an exercise bicycle to a comfortable extent as decided by the subject. During the post exercise relaxation, recordings were taken at regular interval. Fig. 2.9 shows the cross-correlated waveforms by Gattawar [2].

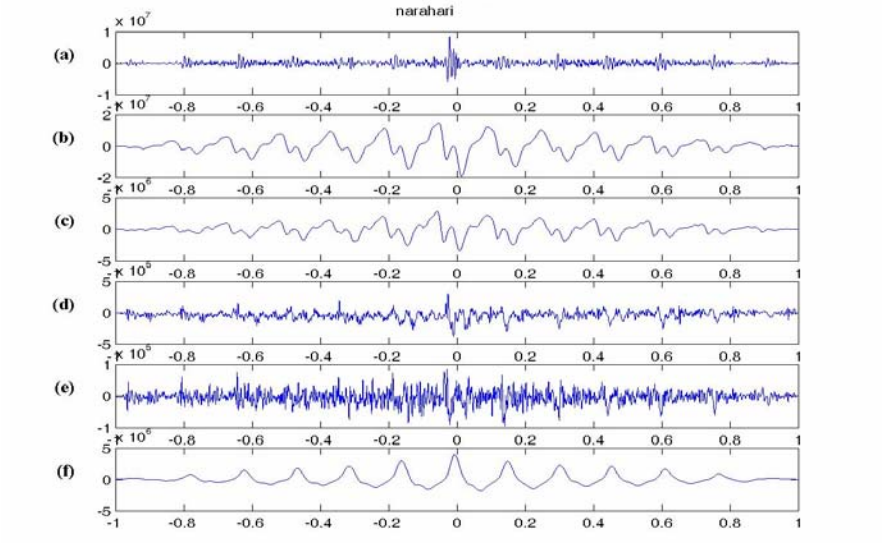


Fig 2.9 (a) ECG-Ist PCG, (b) ECG-RAP, (c) ECG-PPG, (d) Ist PCG-RAP, (e) Ist PCG-PPG, (f) RAP-PPG cross correlated waves [2]

Chapter 3

PULSE WAVE ANALYSIS

3.1 Pulse analysis in traditional medical practice

In ancient time, Chinese physicians were able to determine the internal conditions of the patients by feeling the pulse. In order to make use of this diagnostic tool, the practitioner must learn proper method of taking pulse and categorize it for various pathological conditions. In Traditional Chinese Medicine (TCM) there are three information points on each wrist named *cun, gaun, chi* and they are related to various organs as shown in Fig 3.1 [16].

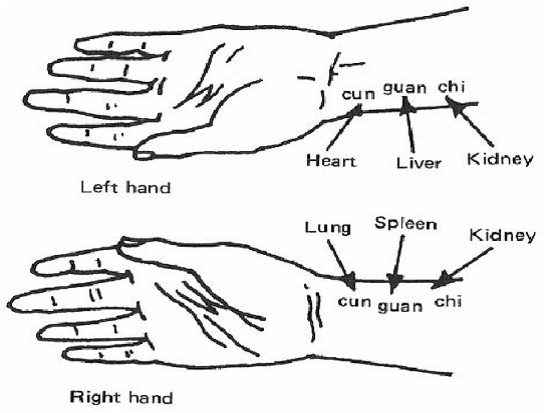


Fig 3.1 TCM pulse points [16]

In the *nadishastra* of *ayurveda,* all bodily processes are believed to be governed by a balance of the 3 *doshas* named *Vata* (air), *Pitta* (fire), and *Kapha* (water). *Vata*, composed of air, governs all movement in the mind and body such as pumping action of heart, breathing process in lung and movements of small intestine. *Vata dosha* is also responsible for mental functions like intuition, imagination, resilience, & sensitivity. *Pitta dosha* is responsible for all the digestion, absorption, assimilation, heat regulation, sweating, and metabolism in the body. *Pitta dosha* is also responsible for mental functions like intelligence, confidence, enterprise, organization, and emotions. *Kapha dosha* provides the material for physical structure to maintains body resistance. *Kapha* lubricates the joints, provides moisture to the skin, helps to heal wounds, fills the spaces

in the body, supports memory retention; gives energy to the heart and lungs and maintains immunity [17].

3.2 Pulse analysis using instruments

The Dudgeon's sphygmograph was used by Upadhyay [6] for pulse sensing and quantitative measurements. The Following parameters were studied,

- Pulse period (time taken by each pulse wave).
- Length of percussion wave from the point of its start to the highest point of its top, which represents the amount of pressure exerted on the blood flow due to the contraction of left ventricle.
- Distance between two nearest peak values of the pulse wave represents the rate of left ventricle contraction.
- Angle of deviation of percussion wave.
- Distance of dicrotic notch from the base line.

Upadhyay studied the above parameters for pulse waves with the pulses classified in accordance with the three *doshas*. Fig 3.2(a), Fig 3.2(b) and Fig 3.2(c) shows the sample pulse wave obtained from normal subjects with *vata*, *pitta* and *kapha dosha* respectively.

From Fig.3.2, the *vata* pulse takes minimum pulse period and has smallest length of percussion wave. It has least angle of deviation and minimum distance of dicrotic notch from the base line of pulse wave. The *pitta* pulse has medium pulse period, highest length of percussion wave, maximum deviation of angle in bending towards the base and maximum distance of dicrotic notch from the base line of pulse wave. The *kapha* pulse indicates maximum pulse period, medium length of percussion wave, medium deviation of angle in bending towards the base and medium distance of dicrotic notch from the base line.

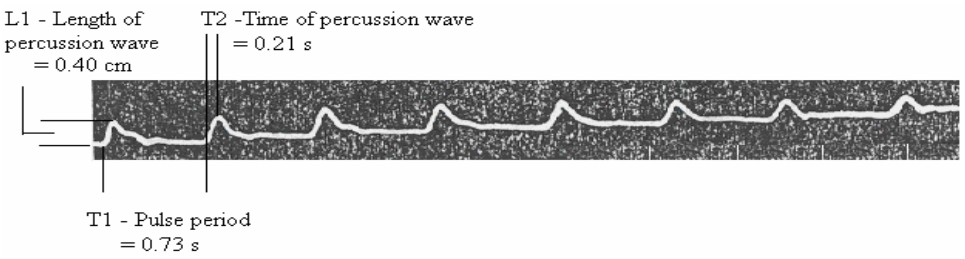


Fig 3.2 (a) *Vata* pulse [6]

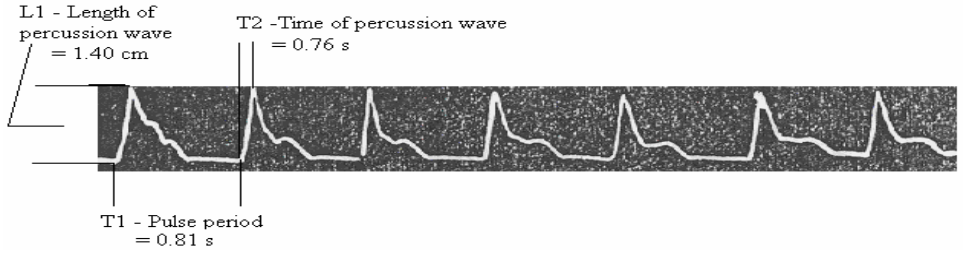


Fig 3.2 (b) *Pitta* pulse [6]

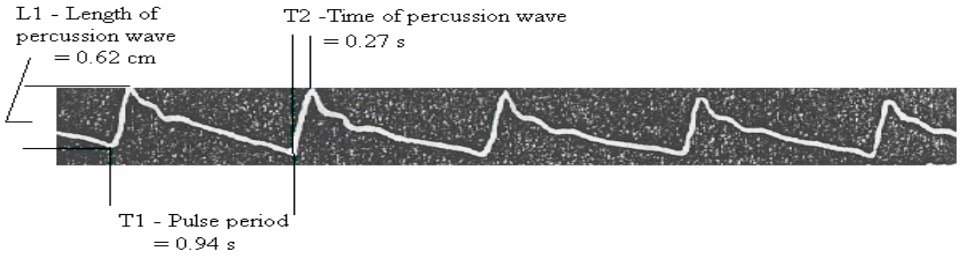


Fig 3.2 (c) *Kapha* pulse [6]

Dasrao et al [18] used Mediwatch for pulse sensing and measurement of arterial pulse rate, systolic and diastolic blood pressure. An acquired pulse waveform is as shown in Fig 3.3. Based on these parameters, the various indices of arterial system can be described, such as augmented pressure, systolic pressure, diastolic pressure, pulse pressure, mean arterial pressure, mean systolic pressure, mean diastolic pressure [18]

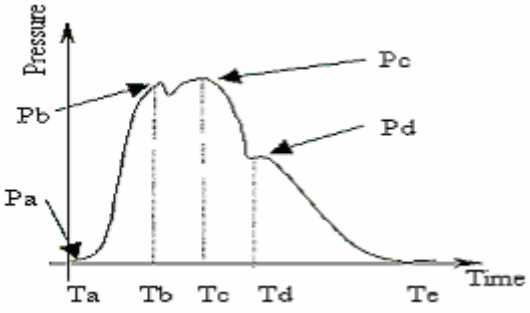


Fig 3.3 Pulse wave analysis using Mediwatch, Pa-foot of pulse, Pb-first shoulder, Pc-second shoulder, Pd-Incisura [18]

3.3 Pulse wave velocity (PWV)

Arterial PWV is index of elasticity (stiffness) of peripheral blood vessels. PWV can be used as marker of artherosclerosis [19]. In hypertension and end stage renal failure the PWV is shown to be an important parameter showing cardiovascular events. The study of Mclaughlin [20] shows that the pulse wave velocity varies over the range of 12 to 15 m/s in stiff peripheral arteries, while in normal artery it varies within a range of 7 m/s to 9 m/s. The arterial stiffness can be affected by both functional and structural changes. Structural changes involves the change in composition of wall of artery i.e. rupture of artery wall or adaptation. Functional changes also affect the PWV, for example the change of blood pressure causes the arterial stiffness to vary. The speed with which waves are traveling depends on the stiffness of the artery along which the pulse wave are traveling. The stiffness changes with age and pathological conditions. Diabetic patients have stiffer arteries then normal persons and elderly persons have stiffer arteries compared to young persons [20].

Calculation of pulse wave velocity by oscillometric method

This method measures the blood pressure by detecting the pulsation of the artery, which is caused by the heart, as the pressure oscillation in the cuff. When the cuff around the upper arm is fully inflated, blood flow stops but pulsation of the artery continue and cause oscillation of the pressure in the cuff. As the pressure in the cuff is decreased slowly, the amplitude of the pressure oscillation in the cuff gradually increases and eventually reaches to a peak. Further decrease of the cuff pressure causes the oscillation amplitude to decrease. Cuff pressure when the oscillation reaches a peak, is taken as the mean arterial pressure (MAP) [20].

In a normal arterial condition, the shape of the oscillometric envelope is like a bell, when arteries are stiffened or atherosclerosed the oscillometric envelope flattens out.

There are choices of sensor to be used for pulse acquisition, such as piezoelectric crystal sensors, photoplethysmograph based sensors, Doppler based sensors [20]. The study of Maguire et al [21] shows that the method of taking pulse from two locations is

more advantageous compare to calculating the pulse transit time method. In the PTT method the measurement of the time delay between features of ECG signal and PPG signal is carried out to calculate the PWV. This method is not accurate as we don't know the path length of pulse wave travel [21]. So they used to take PPG at two points along the same artery as shown in Fig 3.4. In this study, the brachial PPG site having reflective PPG and finger site having transmissive PPG. This allows accurate measurement of PWV over the know path length [21].

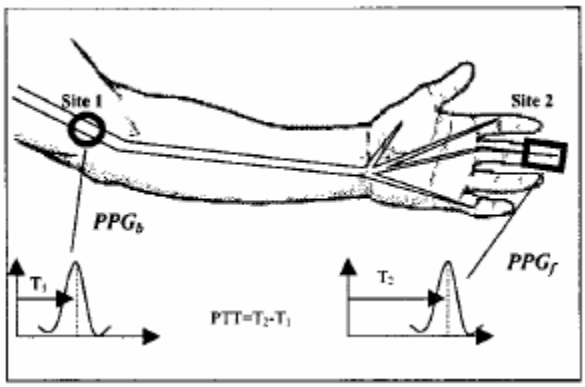


Fig 3.4 PPG sites for taking pulse [21]

The PWV can be calculated by three different methods (i) foot to foot, (ii) peak to peak, (iii) cross-correlation [20].

Foot to foot method: This method requires the identification of the systolic up stroke or foot. The arrival times of the foot of the pulse wave at two positions along the artery are recorded. If the Δt is the difference in the arrival times and the Δs is the distance between two measurement sites, PWV is simply,

$$\text{PWV} = \frac{\Delta s}{\Delta t} \tag{3.1}$$

Peak to peak method: similar to the foot to foot method, except that points of observation are peaks of pulse waves. To calculate PWV using peaks, the location of the peaks must first be determined, so that the transit time of the wave between the peaks can be determined. It was found that the best method of peak detection is the derivative of the curve method. If the first derivative of a curve is zero, then an extreme value can exist, either a peak or a turning point. It is necessary to take the second derivative at this point—if this is also zero, then an extreme value exists.

Cross-correlation PWV: If the arterial pulse at the proximal measurement position is represented by the pressure time series $x_1(t)$ and that at the distal position by $x_2(t)$ and the cross-correlation coefficient is $\Phi_{x1,x2}(\tau)$, then Φ will have a maximum value at some time lag, τ.

The correlation function can be expressed as

$$\Phi_{x1,x2}(\tau) = \left(\frac{1}{T}\right)\int_{-T/2}^{T/2} x_1(t+\tau)x_2(t)d\tau \qquad (3.2)$$

The value of τ at which maximum correlation occurs represents the transit time (Δt) of the pressure wave from position x_1 to position x_2 along the arterial segment. From the separation distance and transit time data the cross correlation arterial pulse wave velocity (CCAPWV) is

$$\text{CCAPWV} = \frac{(x_2 - x_1)}{\Delta t} \qquad (3.3)$$

3.4 Pulse analysis at IIT Bombay

Surve [14] acquired the radial arterial pulse using a piezoelectric sensor and studied its cross-correlation with simultaneously recorded PCG for investigating change in the delay in the cross-correlation peak as an indication of cardiac functioning and arterial blood flow rate. Figure 3.5 shows the cross-correlation of PCG with RAP at different times during post-exercise relaxation on a subject with normal health [14].

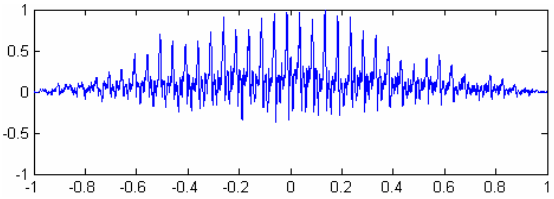


Fig 3.5 (a) Cross-correlation between PCG and pulse at 120 bpm [14]

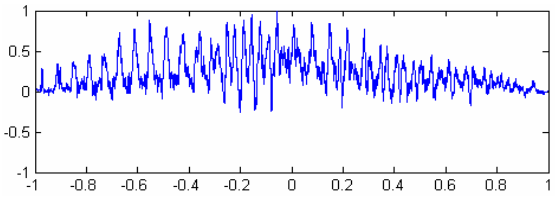


Fig 3.5 (b) Cross-correlation between PCG and pulse at 90 bpm [14]

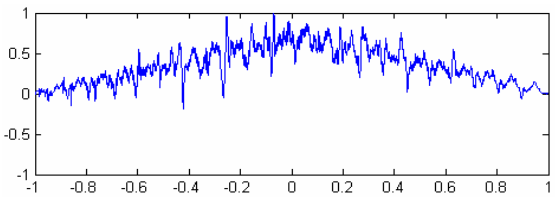


Fig 3.5 (c) Cross-correlation between PCG and pulse at 66 bpm [14]

Gattawar [2] has analysed the pulse in terms of RAP spectral analysis, and cross correlation of RAP with other physiological waveforms such as ECG, PCG, and PPG. RAP is acquired using piezoelectric transducer which is kept in place over the radial artery by closing velcro strap firmly around the wrist. ECG is acquired with limb electrode placement in lead-II configuration. The ECG amplifier used by Gattawar is SECG (manufacturer: Pamtrons, Mumbai). The PCG is been recorded using inverted conical shape sensor, which is positioned over chest to record the mechanical activity of heart. The PCG device used here is SPCG 01 (manufacturer: Pamtrons, Mumbai). PPG is obtained using the circuit developed in SPI lab by Mr. Vinod Pandey [19]. The measurement done at left hand index finger (by reflection mode).

Signal acquisition is done using USB based data acquisition unit (Adlink USBDAQ-9100-MS) at rate of 1 kSa/s with buffer size of 20k (for all four channels) ie. 5 sec recording. Fig 3.6 shows the simultaneous recorded waveforms at rest condition of subject. Each subjects recording done for 5 days within a week [2].

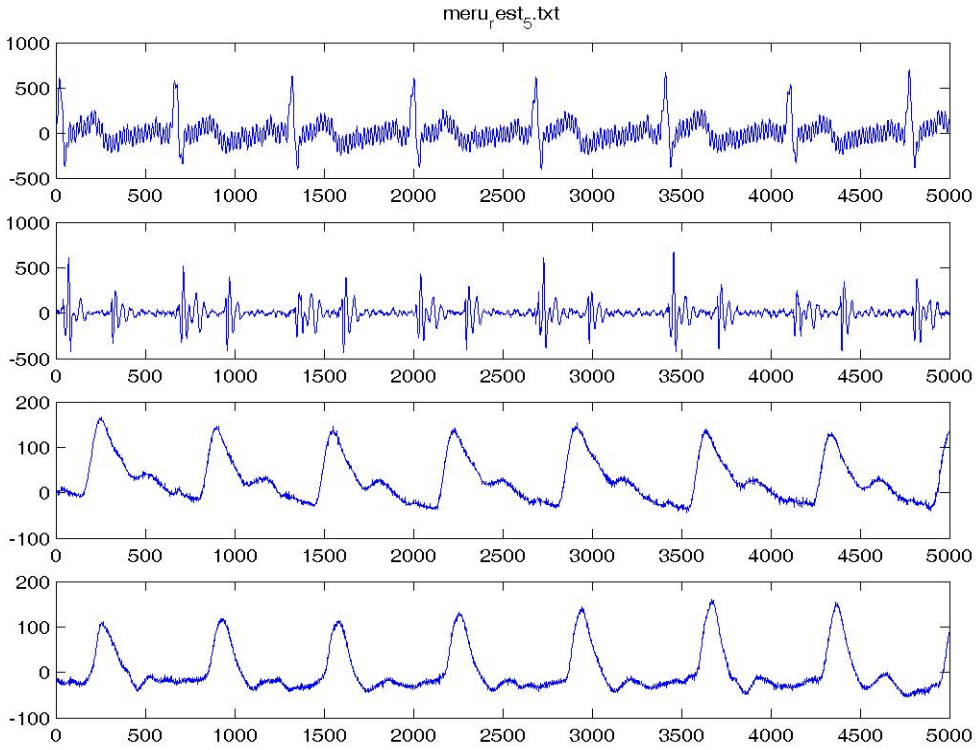


Fig 3.6 Recorded waveform (Y axis: amplitude in arbitrary units, X axis: time in ms). Top to bottom, ECG, PCG, RAP, PPG [2]

Spectral Analysis

Frequency domain power spectrum analysis is robust because the signal is not affected by the phase response of the transducer. Binghe and Jinglin [13] have used the microphone based pulse detecting system for sensing arterial pulse at wrist and analyzed the power spectra of four types (according to traditional Chinese medicine system) of pulses. The pulse has been classified as normal pulse, smooth pulse, wiry pulse and slow-intermittent pulse [13]. The pulse signal was low pass filtered (cut-off frequency 50 Hz) to eliminate operating frequency and other high frequency interference. Further analog pulse signal was digitized by using sampling frequency f_s of 128 Sa/s with recording duration T of 16 s. The power spectrum of pulse signal was obtained by using FFT length of 2048 (= f_s T)

The results shows that (1) all power spectra of pulse signal is distribute in range of 0-40Hz. (2) The spectral energy of pulse is approximately concentrated below about

10 Hz. (3) The spectral energy ratio (SER) of the normal pulse within 10 Hz was above 99% of the total energy, the corresponding values for wiry pulse and smooth pulse were 97% and 83.7% respectively.

Gattawar [2] carried out the spectrum analysis of RAP signal obtained by the piezoelectric transducer. Additionally to quantify the shape of the log power spectrum, mean frequency, standard deviation, and normalized skewness were calculated using formulas given below. For average power spectra, 2.7k sample windows were used with 75% overlap. The sampling rate was 1k Sa/s, the frequency indices corresponding to 10 Hz and 40 Hz are 50 Hz and 200 Hz respectively.

$$\text{Spectral energy ratio (SER)} = \frac{\sum_{k=0}^{k=49} |X(k)|^2}{\sum_{k=0}^{k=199} |X(k)|^2} \tag{3.4}$$

$$\text{Harmonic distortion (HD)} = \sqrt{\frac{\sum_{k=p}^{k=199} |X(k)|^2}{\sum_{k=1}^{k=p-1} |X(k)|^2}} \tag{3.5}$$

(p = 1.5 $\times$ frequency sample corresponding to fundamental frequency)

Log power spectrum $S_d(k)$ is obtained from the squared magnitude spectrum as:

$$S_d(k) = 10 \log |X(k)|^2 \tag{3.6}$$

The mean frequency sample $\bar{k}$ of the log spectrum is given as:

$$\bar{k} = \left| \frac{\sum_{k=0}^{199} k\, S_d(k)}{\sum_{k=0}^{199} S_d(k)} \right| \tag{3.7}$$

Standard deviation of the frequency samples in the log spectrum is given as:

$$\sigma_k = \sqrt{\frac{\sum_{k=0}^{199}(k-\bar{k})^2 S_d(k)}{\sum_{k=0}^{199} S_d(k)}} \tag{3.8}$$

The mean and standard deviation of frequency samples in the log spectrum were converted to frequency value by using:

$$\text{Mean } \bar{f} = \bar{k} f_s / 5000 \tag{3.9}$$

$$\text{S.D. } \sigma_f = \sigma_k f_s / 5000 \tag{3.10}$$

Normalized skewness of the frequency samples in the log spectrum is given as:

$$\text{NSK} = \frac{1}{\sigma_k} \sqrt{\frac{\sum_{k=0}^{199}(k-\bar{k})^3 S_d(k)}{\sum_{k=0}^{199} S_d(k)}} \tag{3.11}$$

We have carried out similar analysis for the RAP signal acquired by pulse wave velocity profiler. The Doppler based instrument is used to sense pulse signal at wrist position. This analysis results are compared with the result of Gattawar [2] study and mentioned in results and discussion section.

The relationship of area under the pulse and heart rate is been studied by us. The recording done by Gattawar [2] is been utilized to calculate the area under the curve in resting state of subject and the after the exercise of two level. The analysis can be used to quantify the cardiac efficiency. The details are given in results and discussion section.

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

Gattawar [2] has recorded pulse signal of 5 volunteer subjects (age: 24 to 28) for 5 days. The recording was done at resting state and post exercise relaxation state. Other physiologically related signals (eg. PPG, PCG, ECG) were also recorded by Gattawar [2]. We have recorded the pulse signal using flow velocity profiler of 3 subjects (age 24 to 26) for 2 days. Two sites recording method is used for calculation of PWV. One flow velocity profiler is placed over the brachial point at elbow and other flow velocity profiler is placed over the radial point at wrist. The output of sensors is fed to computer through USB based data acquisition unit (Adlink USBDAQ-9100-MS).

In this project we have done following analysis.

- Spectral analysis on pulse waveform recorded using flow velocity profiler. The acquired pulse waveform is shown in Appendix A.
- ECG-RAP delay and RAP-PPG delay analysis at resting state and post exercise relaxation state.
- Three different methods (peak-to-peak, foot-to-foot and cross correlation) for delay calculation are compared.
- The study of heart rate and SBP variations due to exercise.

4.2 Results

4.2.1 Spectral analysis

The spectral analysis is carried out on the RAP data recorded by Gattawar [2]. The 5 subjects were rested condition and the sensor used was piezoelectric transducer. The following parameters are found, spectral energy ratio (SER), mean frequency, standard deviation (SD), and normalized skewness (NSK). The equations 3.4, 3.9, 3.10 and 3.11 are utilized for calculation of SER, mean, SD, and SK respectively. Table 4.1 shows the results.

Table 4.1 Spectral parameters of pulse obtained by piezoelectric transducer

	S1	**S2**	**S3**	**S4**	**S5**
SER	99.6	99.9	99.5	99.7	99.7
Mean Freq.	19.0	18.9	18.9	18.8	19.0
SD	11.5	11.6	11.6	11.5	11.4
NSK	2.2	3.4	3.2	3.2	2.9

The spectral analysis is carried out on the pulse signal obtained by flow velocity profiler. The recording was done at resting condition at radial point. The values of parameters are as given in Table 4.2 (The subjects are different from the Table 4.1)

Table 4.2 Spectral parameter of pulse obtained by velocity profiler

	S6	**S7**	**S8**	**S9**	**S10**
SER	99.9	99.9	99.9	99.9	99.9
Mean	18.7	18.0	16.8	18.9	16.9
SD	11.7	11.7	12.1	11.6	12.1
NSK	3.4	4.3	7.1	2.1	7.1

4.2.2 Area under the curve analysis

The area under the pulse curve is calculated for the resting state. The area under the curve of pulse recorded after 5 min and after 10 min of exercise is mentioned in Table 4.3. The area under the curve is calculated using MATLAB function trapz( ). The trapz( ) will convert whole signal in small trapezoids and integration of them will give area under pulse curve. The pulse data is taken from recording of Gattawar [2]. The number of samples is kept constant for the calculation of area under pulse curve. The pulse durations is calculated manually from the pulse wave plot. The relationship of HR, area under the pulse curve and pulse duration is studied.

	Heart Rate			Area under the curve (fixed sample length)			One pulse duration in ms		
	At rest	**After 5 min**	**After 10 min**	**At rest**	**After 5 min**	**After 10 min**	**At rest**	**After 5 min**	**After 10 min**
S1	65	89	82	87652	89779	91139	292	218	201
	83	103	85	154142	98596	54065	303	293	191
	78	142	96	76279	68012	83399	297	196	254
	73	103	87	75208	87257	72958	270	251	171
	65	91	75	87652	97341	84692	325	260	236
S2	79	115	95	51899	11468	261828	298	305	271
	81	108	101	172887	92840	259980	286	258	237
	83	123	96	146860	85875	150500	301	277	240
	78	96	101	91440	98398	99433	200	189	186
	85	103	96	101780	89839	92402	272	228	216
S3	77	108	97	78009	88611	10792	234	153	123
	83	120	95	80783	78902	81557	256	219	207
S4	80	160	109	70160	97490	76342	275	196	217
	73	132	96	85575	94890	44783	272	224	232
S5	106	191	109	318930	178372	83329	277	233	214
	93	128	116	258400	158321	87256	266	210	185

Table 4.3 HR and area under the pulse curve data

The plots of HR and pulse duration analysis are shown below. Here the average values of HR and pulse duration is plotted against the exercise timing for each subject. In the plots X axis: time interval of 5 minutes and Y axis: pulse duration in ms and heart rate in bpm.

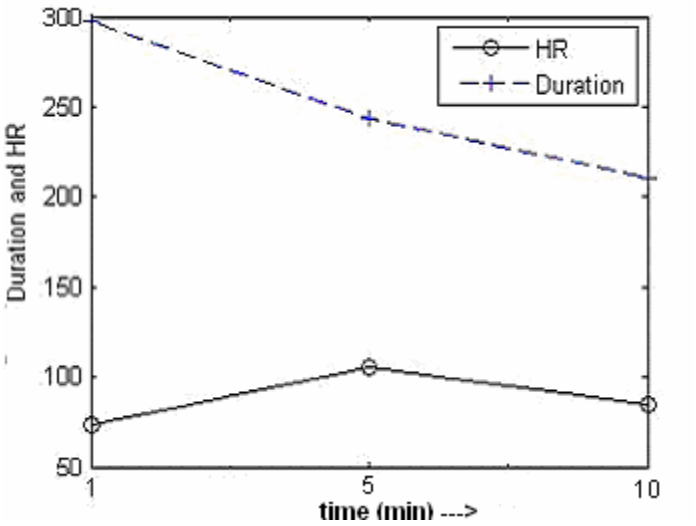


Fig 4.1 HR and pulse duration vs exercise time for S1

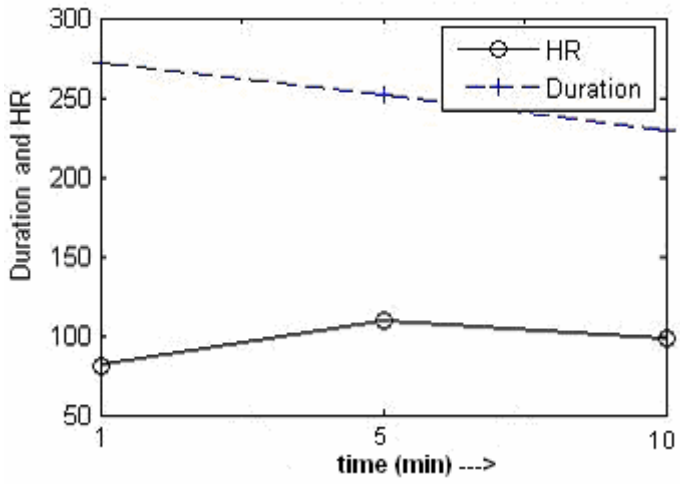


Fig 4.2 HR and pulse duration vs exercise time for S2

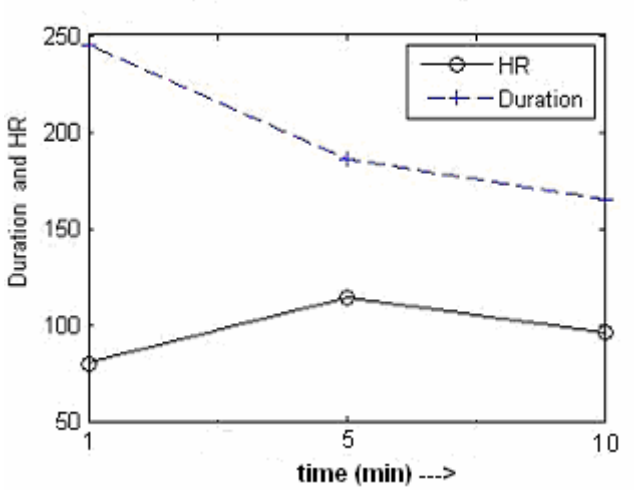


Fig 4.3 HR and pulse duration vs exercise time for S3

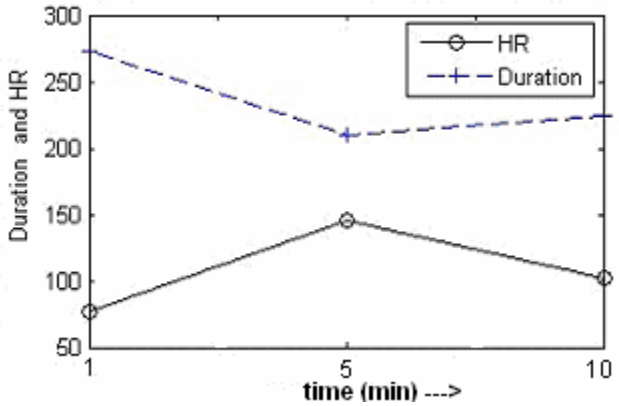


Fig 4.4 HR and pulse duration vs exercise time for S4

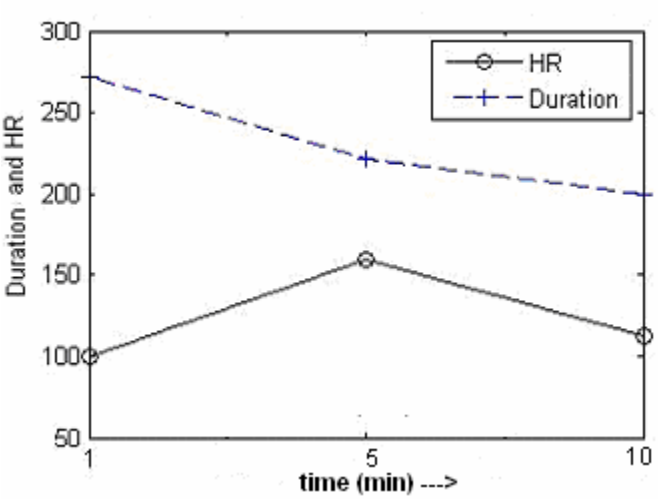


Fig 4.5 HR and pulse duration vs exercise time for S5

4.2.3 Delay, HR and systolic blood pressure analysis

The delay between some physiologically related signals is calculated using cross correlation method. The location of the peak in the cross correlation indicates the delay between two correlated signals. The ratio of correlation sequence's peak and second largest peak is also calculated. The data recording was done at resting state and after 10 minutes of exercise by Gattawar [2]. The analysed data are shown in Table 4.4.

Table 4.4 The delay analysis using cross correlation

	At rest state				**After exercise**			
Subject	**Pulse-PPG**	**Ratio of peaks**	**ECG-Pulse**	**Ratio of peaks**	**Pulse-PPG**	**Ratio of peaks**	**ECG-Pulse**	**Ratio of peaks**
S1	23	1.3	82	1.0	30	1.0	68	1.1
	13	1.2	62	1.0	69	1.4	84	1.1
	16	1.4	72	1.2	25	1.3	73	1.2
	49	1.3	85	1.1	65	1.4	89	1.4
	23	1.3	82	1.0	28	1.2	77	1.6
S2	20	1.2	61	1.3	5	1.2	69	1.5
	8	1.3	71	1.2	6	1.1	46	1.2
	16	1.2	64	1.0	10	1.2	55	1.1
	19	2.4	61	1.0	16	1.2	116	1.0
	9	1.4	63	1.0	28	1.2	64	1.1

The two site method is implemented for the calculation of time delay between different sites along same artery. One flow velocity profiler is placed over brachial point and other is placed over the radial point. The peak-to-peak, foot-to-foot and cross correlation methods are implemented to calculate delay. The results are shown in Table 4.5.

Table 4.5 Time delay analysis using different methods

	Peak to peak	Foot to foot	Cross correlation	Average of all
S6	19	36	17	24
	18	29	12	19
	25	38	10	24
S7	34	57	22	37
	24	22	18	21
S8	36	33	15	28
	36	34	13	27

The heart rate and delay analysis

Gattawar [2] had recorded radial arterial pulse (RAP) waveform along with other physiological signals like finger photoplethysmogram (PPG), phonocardiogram (PCG), Electrocardiogram (ECG) for five days of five subjects.

In normal condition average ECG-RAP delay is 7.9 ms, average delay between RAP and PPG is 2.4 ms. The delay patterns probably indication of different patterns in changes in blood supply during exercise and the relaxation phase.

The ECG-RAP delay analysis is done for 5 subjects. The variation of ECG-RAP delay is shown in Table 4.6 below. The data in each cell is mean value of 5 days. The Fig. 4.6 is plot of the delays of 5 subjects versus stress level. The time duration between recording was 3 to 4 minutes according to convenience of subject.

Table 4.6 Variations of ECG-RAP delays

	ECG-RAP Delays in ms				
	At rest	**After time duration 1**	**After time duration 2**	**After time duration 3**	**After time duration 4**
S1	44.8	25.9	33.5	19.5	22.5
S2	51.9	94.8	43.7	52.2	47.6
S3	51.4	37.7	50.9	52.8	48.8
S4	12.5	9.5	12.4	11.7	11.9
S5	46.2	19.8	20.1	22.1	23.5

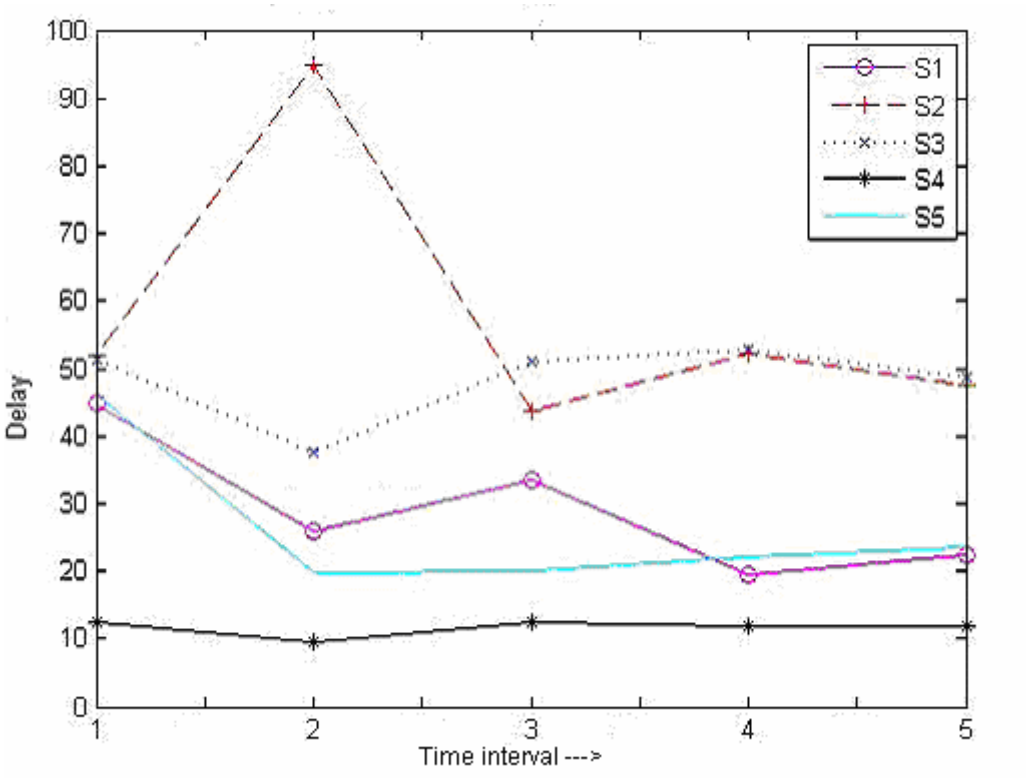


Fig 4.6 ECG-RAP delays vs exercise time intervals (X axis: Time interval of 3-4 minutes, Y axis: delays in ms)

The analysis of RAP-PPG delay was carried out and the results are as shown below. The mean for different stress levels for 5 days was calculated and the values are given in Table 4.7. Fig. 4.7 is plot of the delays of 5 subjects versus exercise time intervals.

Table 4.7 Variations of RAP-PPG delays with exercise time intervals

	RAP-PPG Delays in ms				
	At rest	**After time duration 1**	**After time duration 2**	**After time duration 3**	**After time duration 4**
S1	4.7	4.8	4.7	6.7	8.5
S2	6.5	5.5	12.7	4.1	7.7
S3	3.8	7.2	6.9	5.6	6.4
S4	2.7	4.0	2.9	2.8	2.9
S5	2.9	2.4	2.4	3.0	2.6

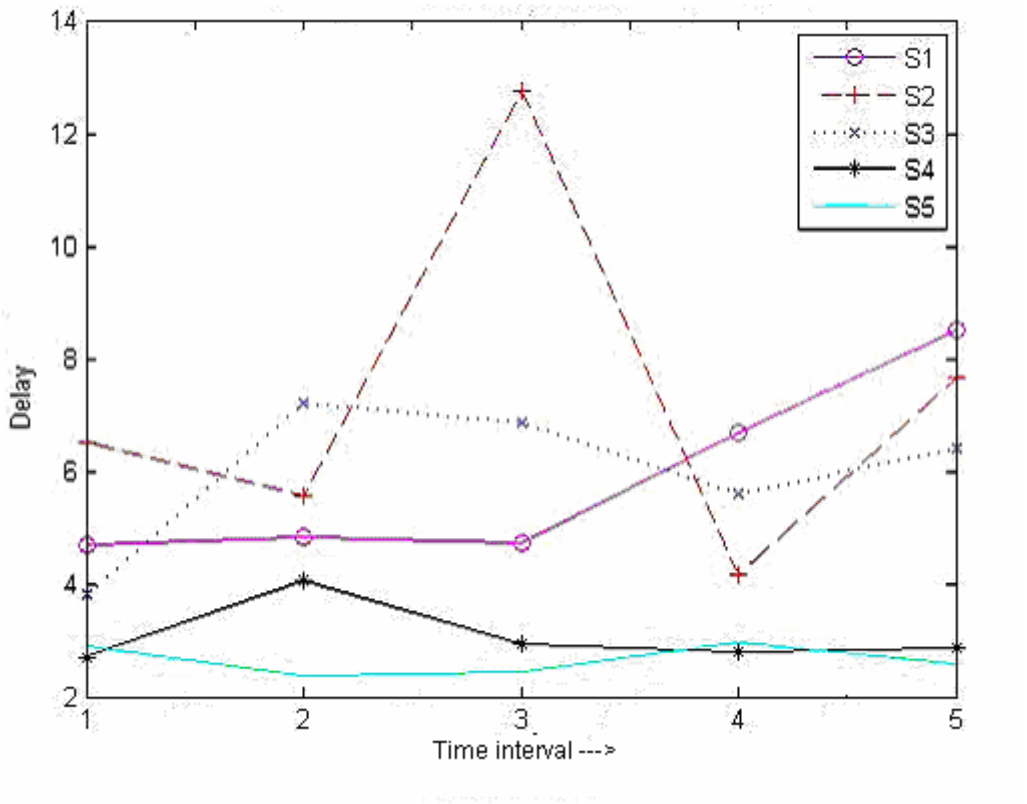


Fig 4.7 RAP-PPG delays vs exercise time intervals (X axis: Time interval of 3-4 minutes, Y axis: delays in ms)

The variation of heart rate along with ECG-RAP and RAP-PPG delay due the exercise activity is studied. The data in each cell of Table 4.8 is mean value of 5 days recorded by Gattawar [2] and the plot of the same is shown in Fig 4.8.

Table 4.8 HR and delay variation due to exercise of subject 5

	At rest	**Post exercise relaxation**			
		After time 1	**After time 2**	**After time 3**	**After time 4**
HR(bpm)	80.0	110.0	97.2	96.0	96.6
ECG-RAP(ms)	46.2	19.8	20.1	22.1	23.5
RAP-PPG(ms)	2.9	2.3	2.4	3.0	2.6

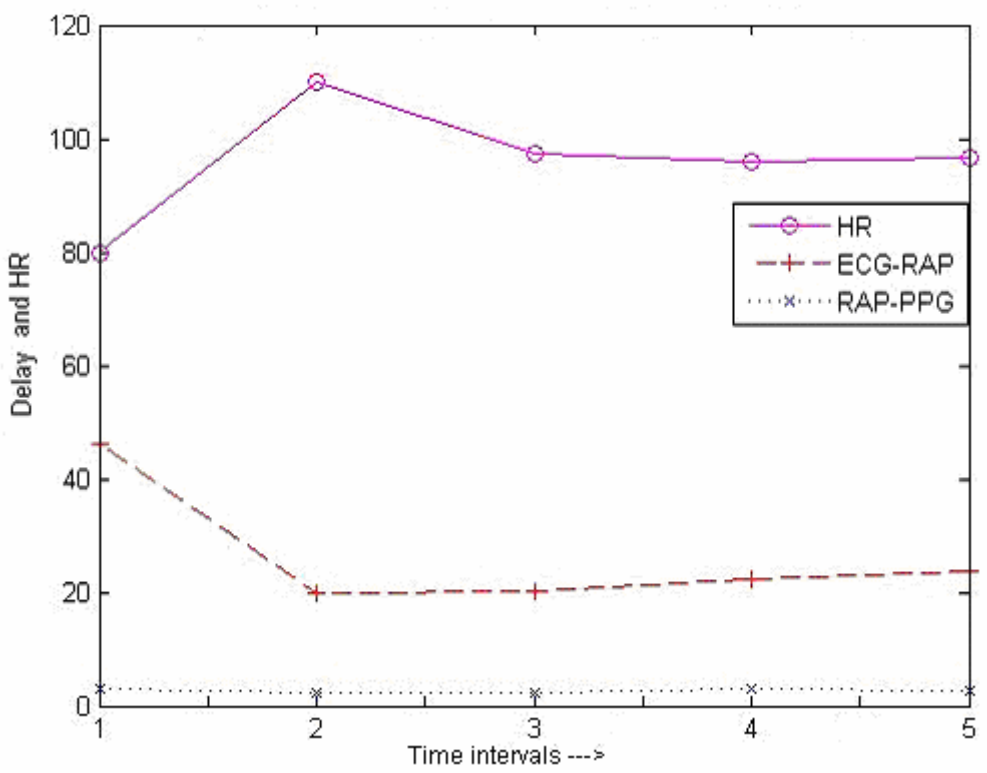


Fig 4.8 HR and delays vs exercise time interval (X axis: Time interval of 3-4 minutes, Y axis: delays in ms and heart rate in bpm)

The HR variation due to exercise is shown in Table 4.9. The recording was done after time interval of 3-4 minutes according to convenience of subject. The values are mentioned in Table 4.9 and the plot of the same is shown in Fig 4.9 below.

Table 4.9 HR variations due to exercise for 5 subjects

	At rest	**After various exercise levels**			
		At time int.1	**At time int.2**	**At time int.3**	**At time int.4**
S1	80	100	95	84	84
S2	83	103	99	84	85
S3	78	142	101	96	96
S4	96	103	98	89	87
S5	65	91	89	82	75

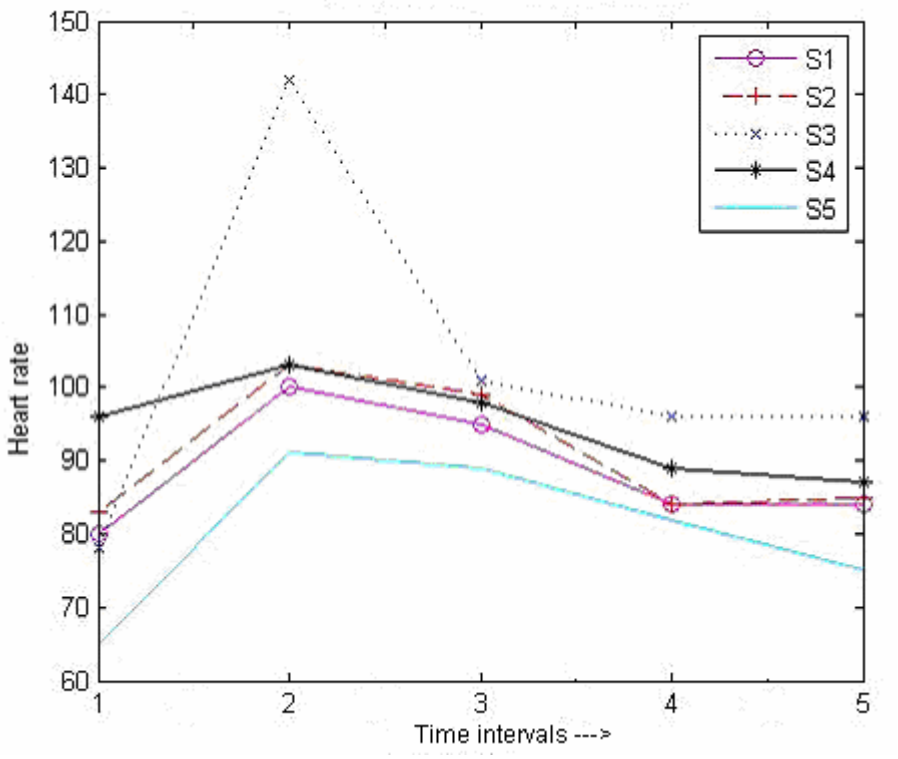


Fig 4.9 HR variations due to exercise for 5 subjects (X axis: Time interval of 3-4 minutes, Y axis: heart rate in bpm)

Systolic blood pressure analysis

The data recorded by Gattawar [2] has been analyzed at rest and post exercise relaxation for 5 subjects for 5 days in week. The time interval between recordings was 5 minutes. The data shown in table 4.10 is mean value of 5 days. The plot of the same is displayed in Fig 4.10.

Table 4.10 SBP variations due to exercise for 5 subjects

SBP	S1	S2	S3	S4	S5
At rest	103.8	109.8	119.6	158.0	123.0
After 5 min	116.0	162.0	144.2	184.0	145.4
After 10 min	106.0	116.0	115.0	156.8	120.8

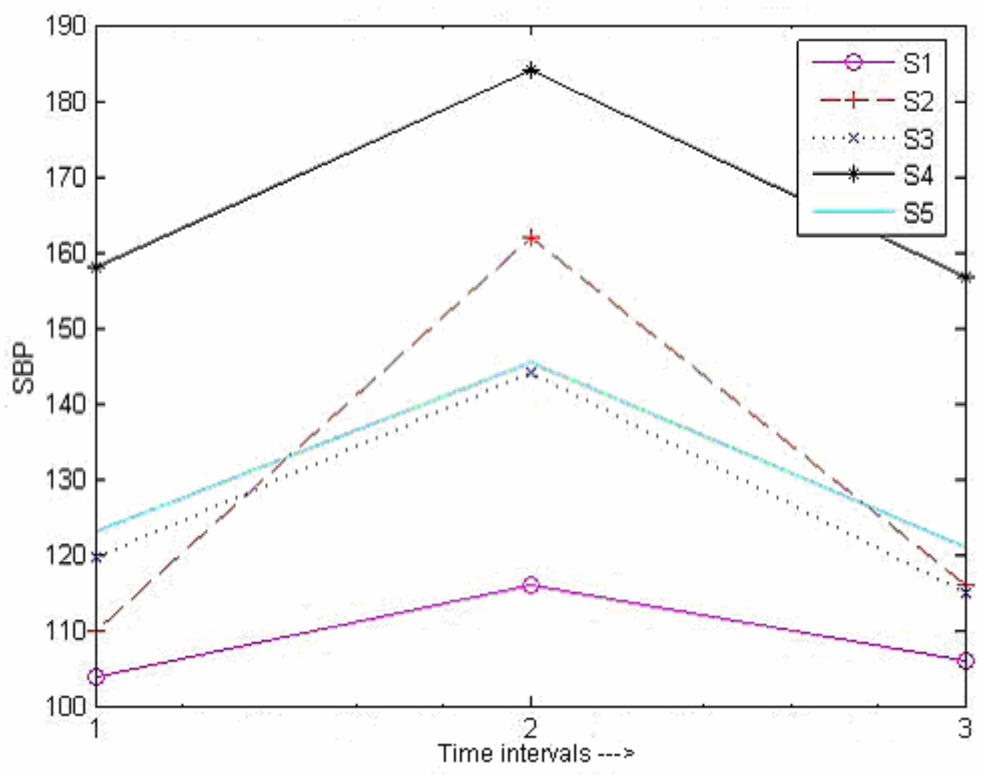


Fig 4.10 SBP variations due to exercise for 5 subjects (X axis: Time interval of 3-4 minutes, Y axis: systolic blood pressure in mm of Hg)

The analysis of SBP for S2 for 5 days is carried out and results are shown in Table 4.11 and plotted in Fig 4.11.

Table 4.11 SBP variations due to exercise for S2

SBP	S1	S2	S3	S4	S5
At rest	120	112	94	118	105
After 5 min	160	170	186	164	130
After 10 min	120	113	127	112	112

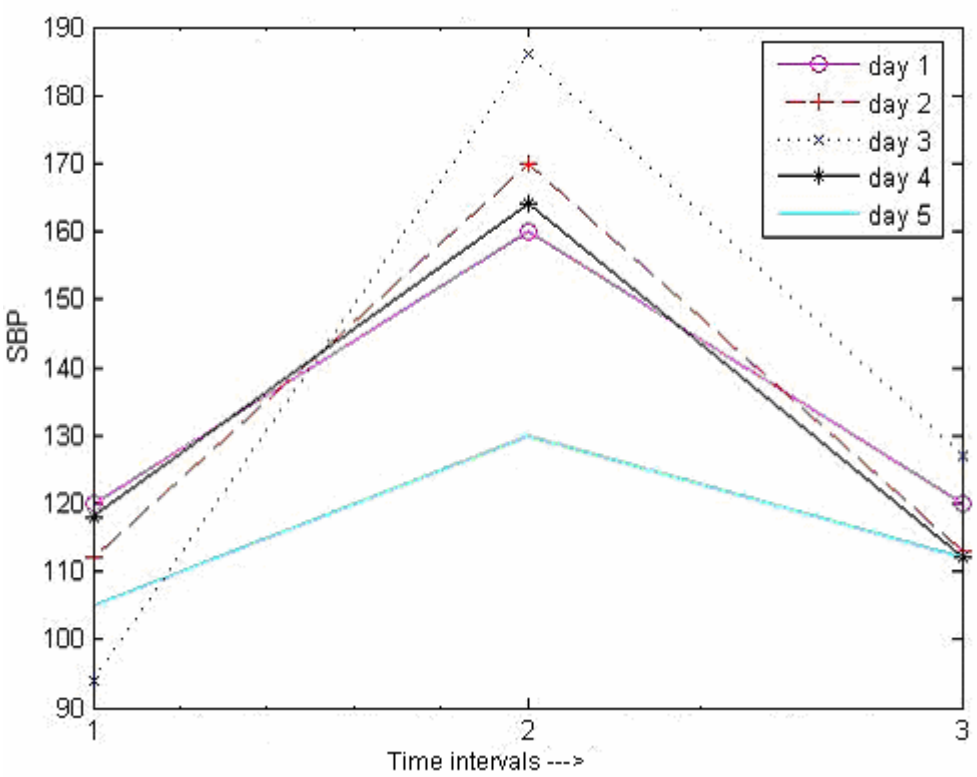


Fig 4.11 SBP variations due to exercise for S2 (X axis: Time interval of 3-4 minutes, Y axis: systolic blood pressure in mm of Hg)

Heart rate, systolic blood pressure, ECG-RAP delay, RAP-PPG delay are shown in Table 4.12. The recording was done under rest condition by Gattawar [2]. The plots of various parameters along days are shown in Fig 4.12, 4.13, 4.14, 4.15 for S2, S3, S4, and S5 respectively.

Table 4.12 SBP, HR and delays at rest condition for 5 subjects

	Day	SBP (mm of Hg)	HR (bpm)	ECG-RAP delay (ms)	RAP-PPG delay (ms)
S1	**1**	107	80	49.0	4.5
	2	94	83	44.0	2.0
	3	100	78	46.0	2.9
	4	111	96	36.0	10.0
	5	107	65	49.0	4.0
S2	**1**	120	98	50.0	3.0
	2	112	85	53.0	6.0
	3	94	76	58.0	6.0
	4	118	91	53.0	6.0
	5	105	83	45.5	11.5
S3	**1**	133	123	58.0	4.0
	2	113	80	49.0	4.0
	3	96	73	50.0	3.0
	4	109	93	49.0	6.0
	5	117	83	51.0	2.0
S4	**1**	156	106	13.7	3.1
	2	151	106	13.2	2.9
	3	171	93	14.0	2.6
	4	161	87	16.9	2.5
	5	152	101	4.9	2.6
S5	**1**	118	75	71.0	2.4
	2	118	81	66.3	2.1
	3	125	83	66.0	3.4
	4	140	78	13.8	4.5
	5	113	85	14.0	2.2

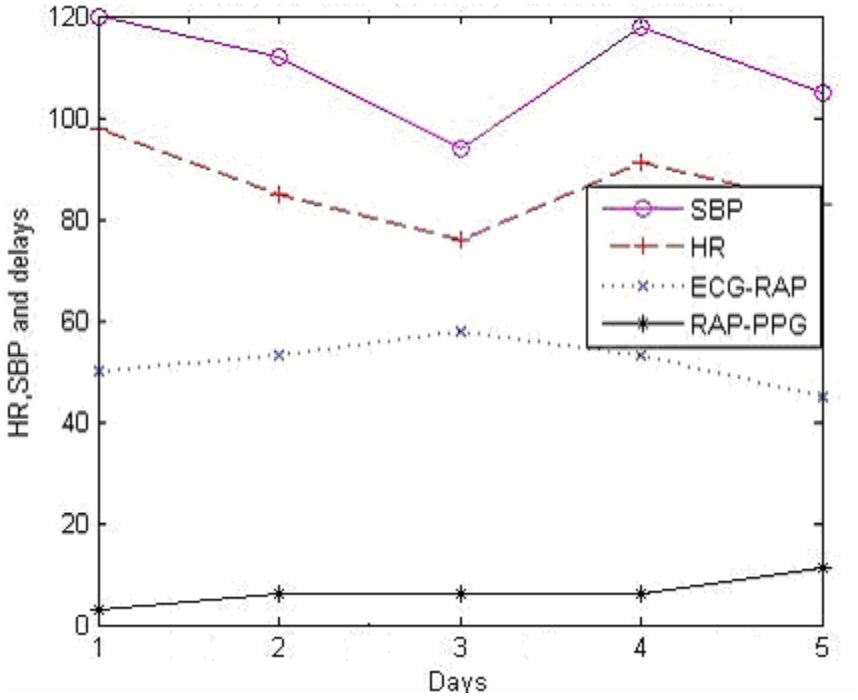


Fig 4.12 HR, SBP, delay variations along the days for S2

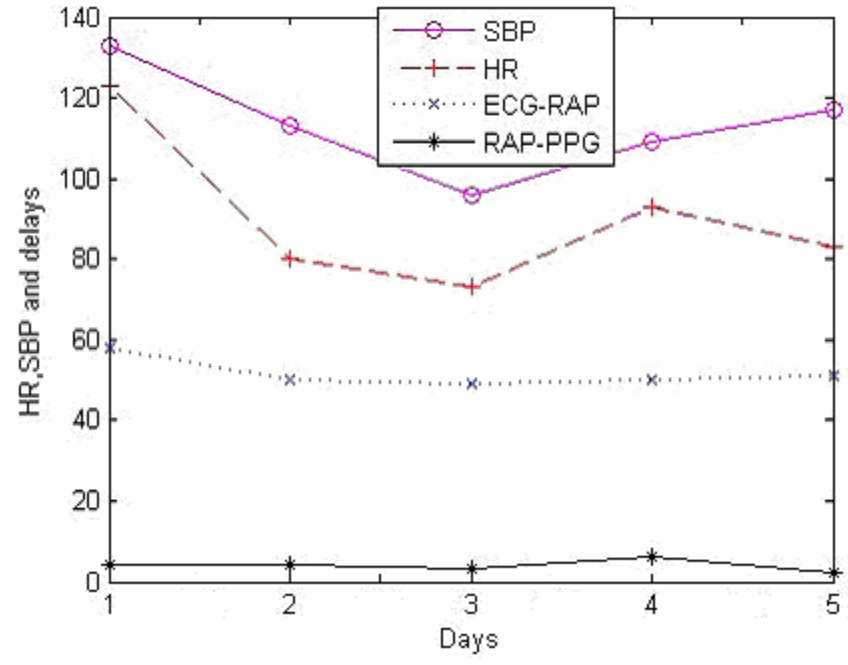


Fig 4.13 HR, SBP, delay variations along the days for S3

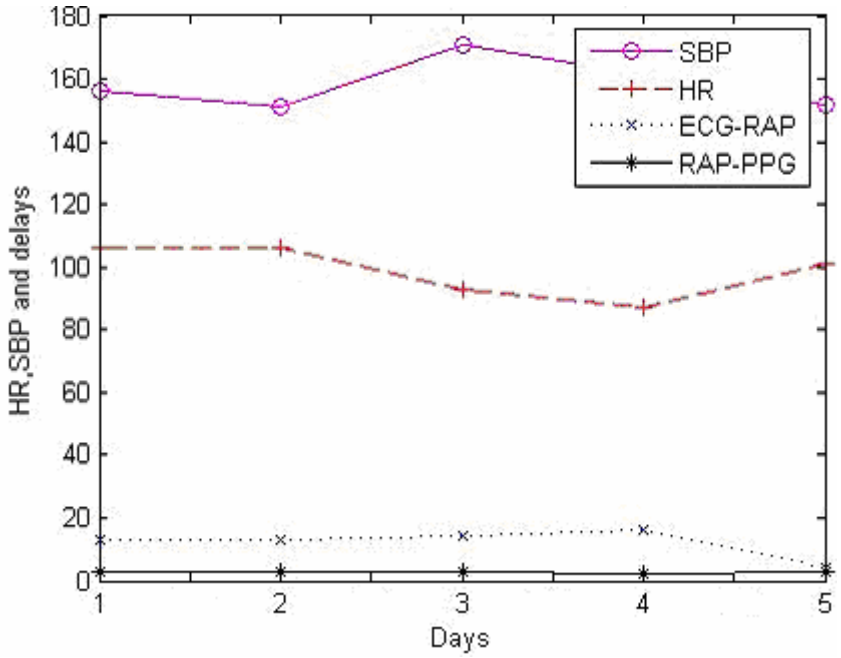


Fig 4.14 HR, SBP, delay variations along the days for S4

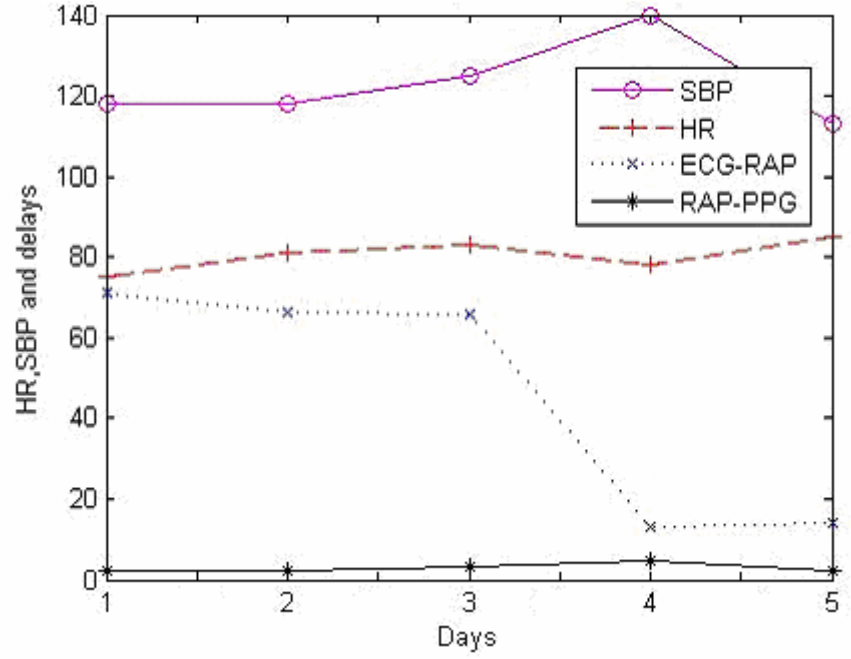


Fig 4.15 HR, SBP, delay variations along the days for S5

4.3 Discussion

The heart rate of all the subjects is much higher than normal heart rate (72 bpm) at resting condition. For four of the subjects the blood pressure readings can be considered normal. However for the subject S4, the blood pressure record (both systolic and diastolic) was much higher than the normal on the all the days. SER values from the spectral analysis of pulse waveform are constantly about or above 99%, which indicate normal pulse according to Binghe and Jinglin's Study [13]. The three statistical measures on log power spectrum shows very narrow variation across days and across subjects. Averaged across subjects, the mean frequency is 17.87 Hz, standard deviation is 11.83 Hz and normalized skewness is 4.84. The results are similar to results obtained by Gattawar [2].

Under the pre exercise condition, there was a variation across the days and across the subjects for all delay values. It is noticeable that for subject S4, with high BP, all the delay values are relatively smaller. For other four subjects ECG-RAP delay varies over the range of 44 ms to 52 ms. While for the subject S4 it is unusually low, 13.2 ms. The RAP-PPG delay varies over the range of 2.74 ms to 6.4 ms. The delay obtained by two site recording method varies over range of 19 ms to 38 ms. This delay represents the time taken by pulse wave to travel from brachial point to radial point.

Under the exercise condition the ECG-RAP delay and RAP-PPG delay does not show any constant pattern across the days and across the subjects. ECG-RAP delay: for the subject S3, there is large increase in value followed by decrement due to exercise. Other subject's delay values show initial decrement in value and then recovery. RAP-PPG delay: for subject S5 the delay decreases initially and then it increase slowly. For subject S2 the variations are very large. For other subjects delay value initially increase and then decrease slowly. The area under the pulse curve analysis shows, initially with exercise the pulse duration decreases and area under the curve (with fixed number of samples) increases. This area under the curve increment might be considered as to fulfill the high oxygen requirement. The HR initially increase with exercise and slowly steady down to above normal level. The SBP increases initially with exercise for all subjects and then it settles down.

Chapter 5

SUMMARY AND FUTURE SCOPE

In this project, the analysis of pulse waveform is carried out by means of spectral analysis and cross correlation of pulse signal with other physiologically related signals. The pulse signals have been earlier acquired by Gattawar [2]. The analysis of delays between various physiological related signals is carried out at resting condition and after various state of exercise. The variation of area under the pulse wave, the variation of heart rate, and SBP variation after the exercise is studied. In this exploratory study the data acquired from normal healthy subjects with no known cardiovascular diseases. The exact level of exercise or timing of recording is not controlled. Hence no conclusion can be drawn.

Some suggestions for future work are:

(i) Recording of pulse wave using blood velocity profiler for more number of subjects with classification of subjects according to HR, BP and other known problems, and under controlled condition,

(ii) Pre-processing of waveforms (particularly ECG, PCG) for enhancing the cross-correlation peaks.

(iii) Recording of the pulse signal of some patients having kidney diseases or cardiovascular diseases.

Appendix A

Cross Correlation Analysis

The cross correlation is used to measure the degree to which two signals are similar. The cross correlation is calculated using MATLAB function xcorr( ). If x_1 and x_2 are two M length vectors, the length of cross correlation sequence will be $2M$-1. If x_1 and x_2 are different length, the shortest one is zero-padded [23].

$$r_{x_1,x_2}(l) = \sum_{n=-\infty}^{n=\infty} x_1(n+l)x_2(n); l = 0, \pm 1, \pm 2, \ldots \qquad (1)$$

If the two sequences are totally uncorrelated, the cross-correlation will have a low value for all 'l'. In case both waveforms have the same signal as the strong constituent, the delay for which maximum peak of cross-correlation occurs indicates the delay between the two sequences. The cross-correlation of $x_1(n)$ and its delayed version $x_1(n + d)$ yield a result that has a peak at $n = -d$.

Verification of program:

Various synthesized waveforms are used to verify the program. Sine pulse, square pulse, decaying sine pulse, and continuous sine wave are generated. The cross correlation with the delayed version of each is found. The 10 samples and 20 samples delay has been added to original signal, the cross correlation show the peak value at actual delay value between two sequences. For accuracy verification random noise has been added to delayed sequence. The cross correlation shows the actual value of delay irrespective of noise been added. The noise level is varied with same delay value and resultant plots are shown in figure below.

The two peaks of correlation sequence is found using automatic peak detection algorithm. Suppose $x(n)$ is correlation sequence and its peak is at sample value x_p. Now new sequence is generated named $x'(n)$. The new sequence is having samples of $x(n)$ after sample value x_p. Again the peak value of $x'(n)$ is found, which is the second largest peak of the original correlation sequence. Now the ratio of two peak value is calculated and shown in figure given below.

Fig A.1 and A.2 shows the normal sine pulses with delay of 10 and 20 samples respectively. Note that cross correlation peaks are at 10 and 20 in Fig A.1 and A.2 respectively.

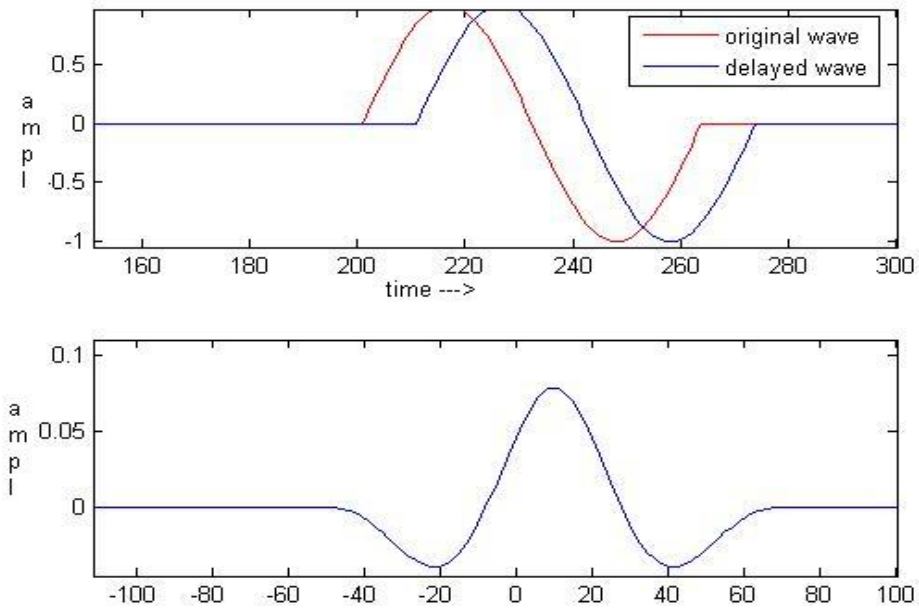


Fig A.1 Normal sine pulse & 10 samples delayed sine pulse and its cross correlation plot

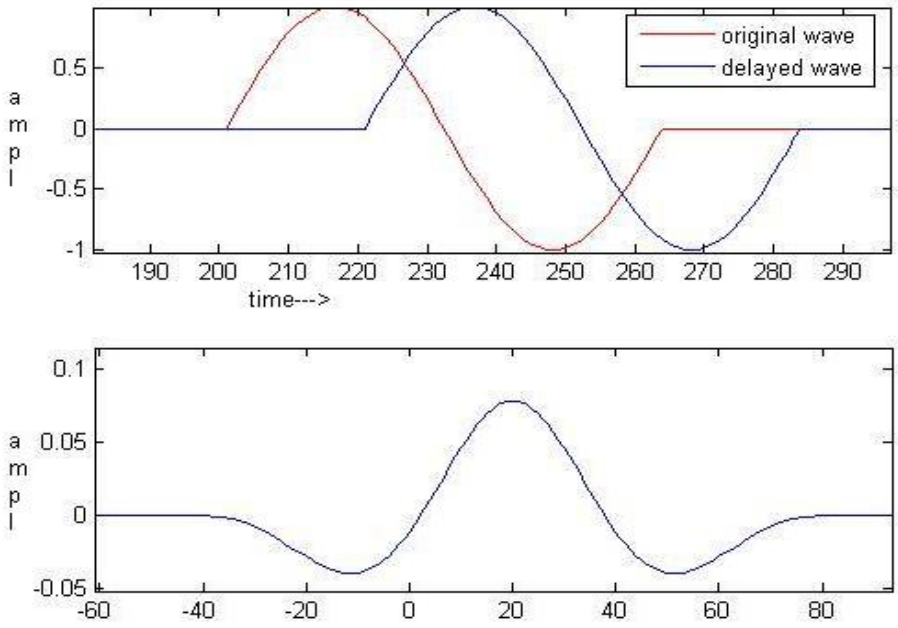


Fig A.2 Normal sine pulse & 20 samples delayed sine pulse and its cross correlation plot

Fig A.3 and A.4 shows normal sine pulse and noisy sine pulse with 10 samples delay. The noise added was random noise 0.5 unit and 1 unit in delayed pulse. The location of peaks in the cross correlation are at 10 in Fig A.3 and A.4.

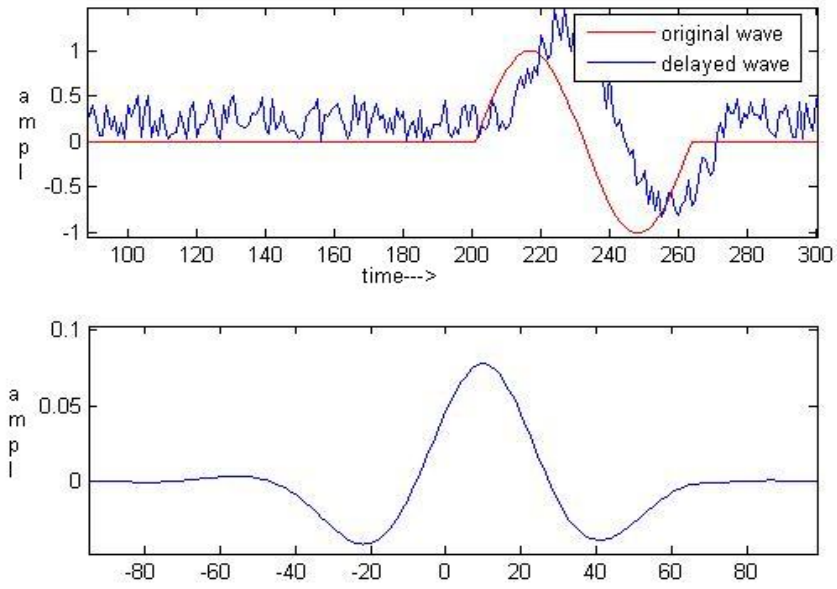


Fig A.3 Normal sine pulse and 10 samples delayed pulse with noise (0.5 unit) and its cross correlation (SNR=16.96)

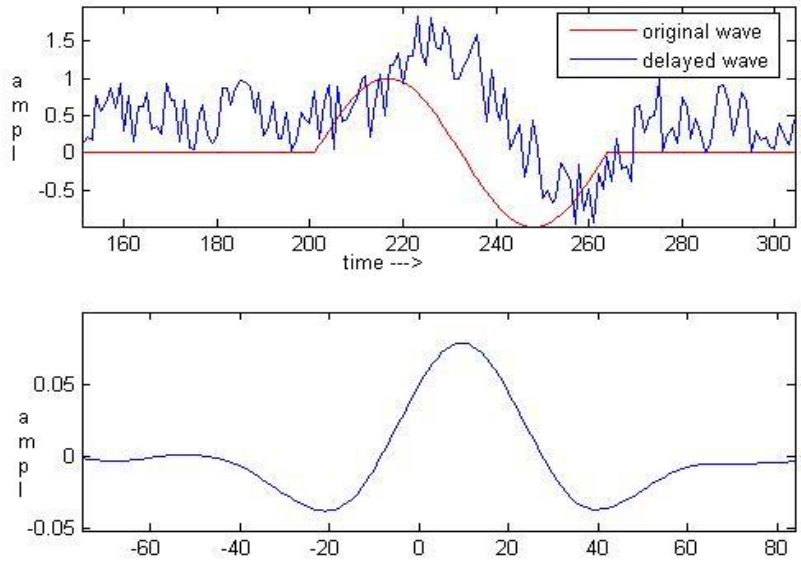


Fig A.4 Normal sine pulse and 10 samples delayed pulse with noise (1 unit) and its cross correlation (SNR=4.43)

Fig A.5 and A.6 shows the normal square pulses with delay of 10 and 20 samples respectively. Note that cross correlation peaks are at 10 and 20 in Fig A.5 and A.6 respectively.

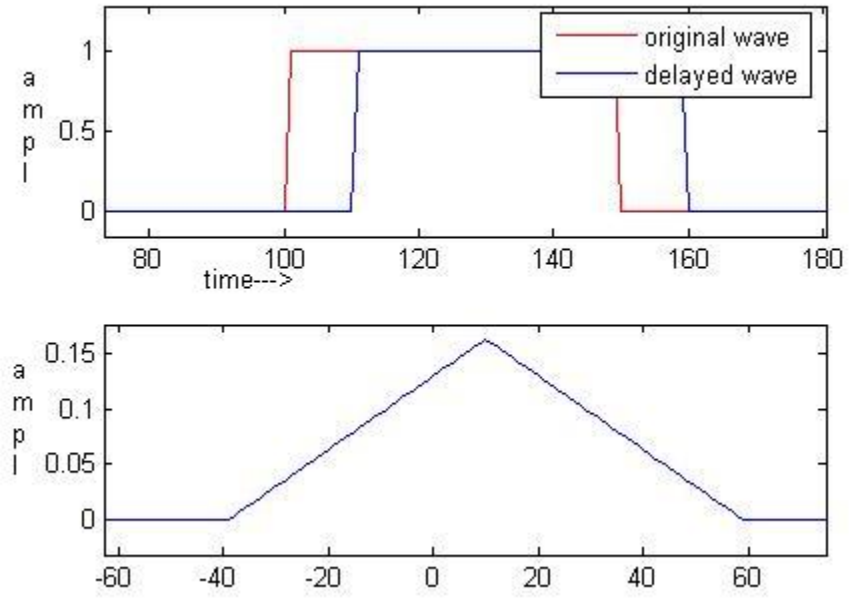


Fig A.5 Normal square pulse & 10 samples delayed square pulse & cross correlation plot

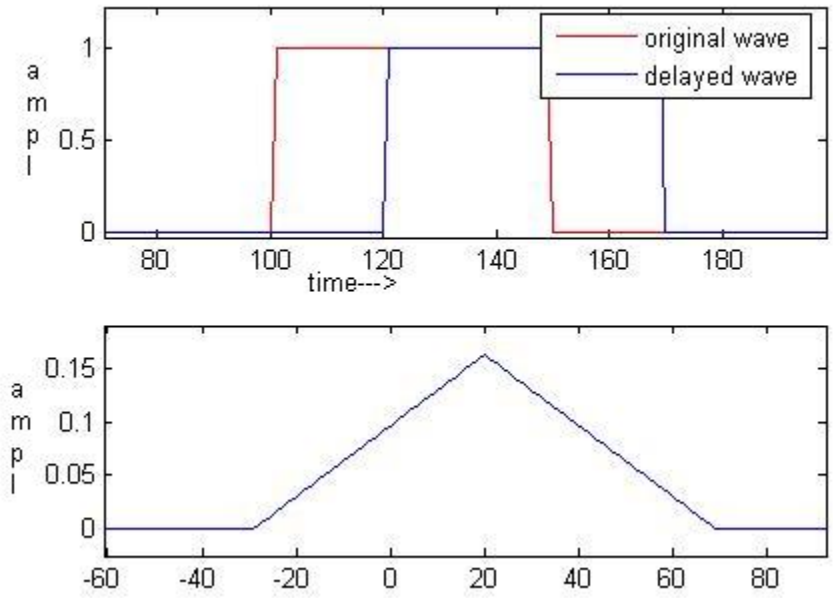


Fig A.6 Normal square pulse & 20 samples delayed square pulse & cross correlation plot

Fig A.7 and A.8 shows normal square pulse and noisy square pulse with 10 samples delay. The noise added was random noise 0.5 unit and 1 unit in delayed pulse. The location of peaks in the cross correlation are at 10 in Fig A.7 and A.8.

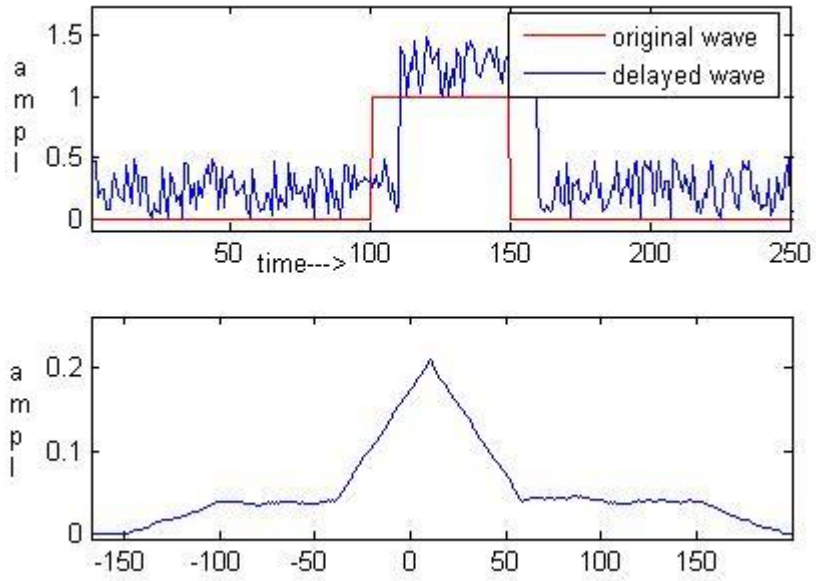


Fig A.7 Normal square pulse and 10 samples delayed pulse with noise (0.5 unit) and its cross correlation plot (SNR=26.10)

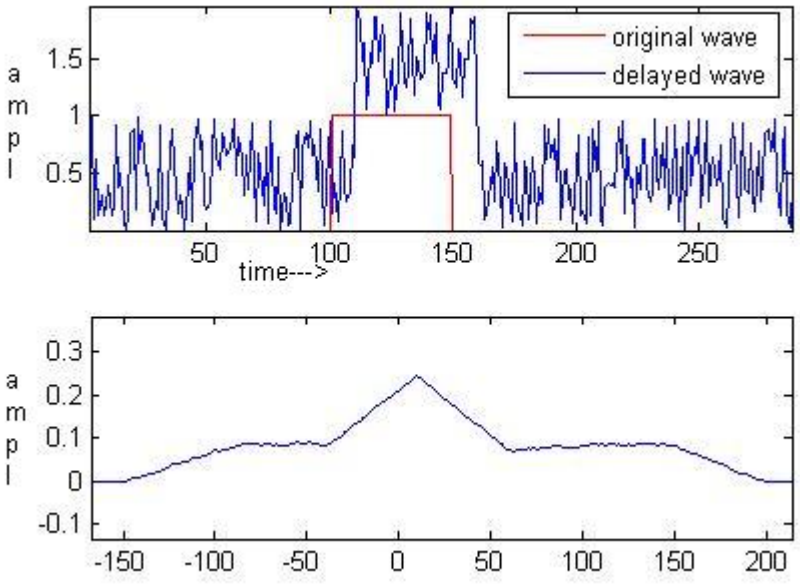


Fig A.8 Normal square pulse and 10 samples delayed pulse with noise (1 unit) and its cross correlation plot (SNR=11.98)

Fig A.9 and A.10 shows the decaying sine pulses with delay of 10 and 20 samples respectively. Note that cross correlation peaks are at 10 and 20 in Fig A.9 and A.10 respectively.

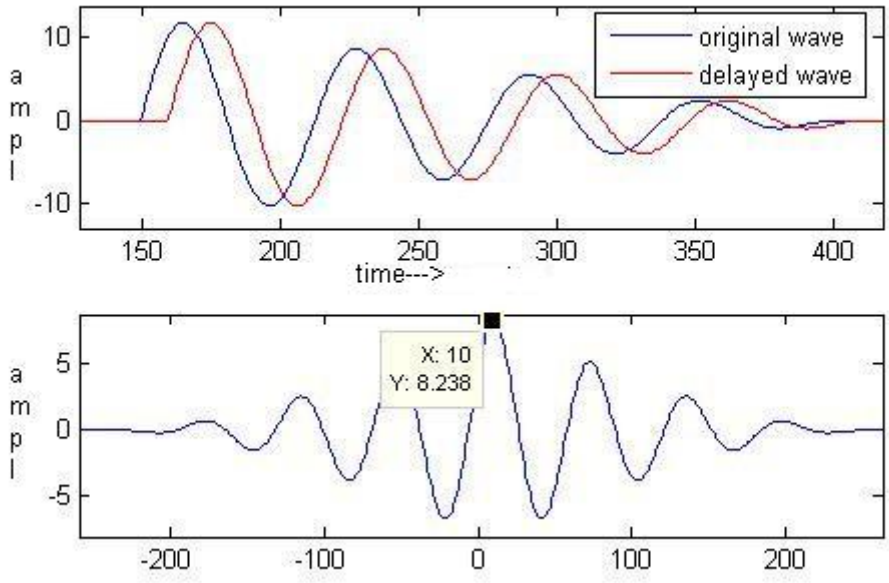


Fig A.9 Normal decay pulse & 10 samples delayed pulse and cross correlation plot (Correlation sequence' peaks ratio 1.58)

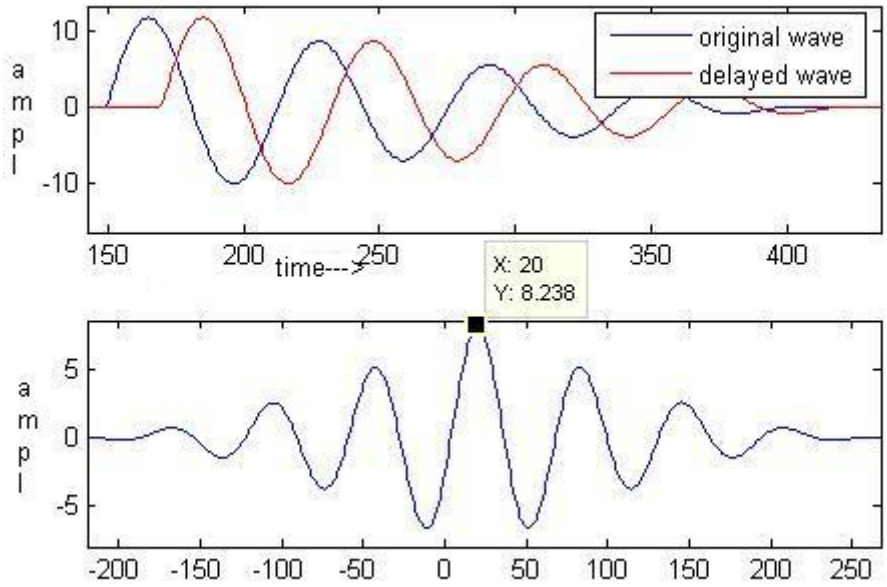


Fig A.10 Normal decay pulse & 20 samples delayed pulse and cross correlation plot (Correlation sequence' peaks ratio 1.58)

Fig A.11 and A.12 shows decaying sine pulse and noisy sine pulse with 10 samples delay. The noise added was random noise 0.5 unit and 1 unit in delayed pulse. The location of peaks in the cross correlation are at 10 in Fig A.11 and A.12.

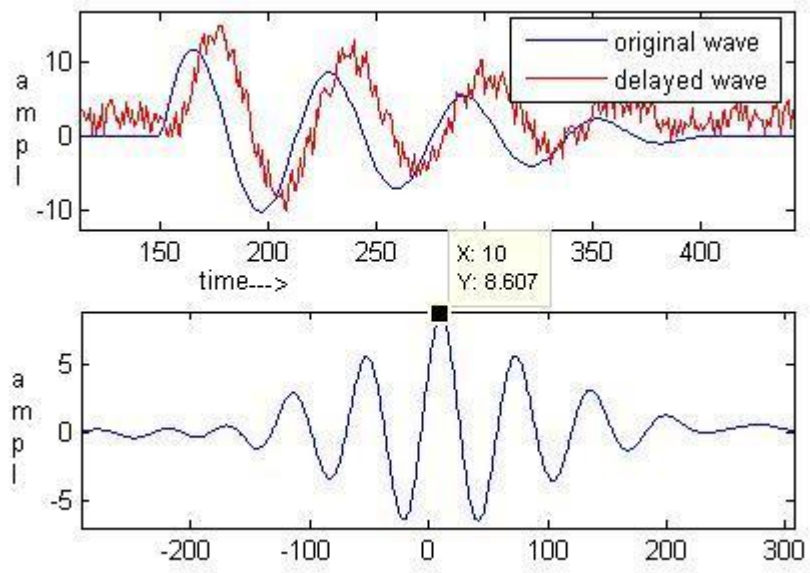


Fig A.11 Normal decay pulse and 10 samples delayed pulse with noise (0.5 unit) and its cross correlation plot (SNR=23.37, Correlation sequence' peaks ratio 1.57)

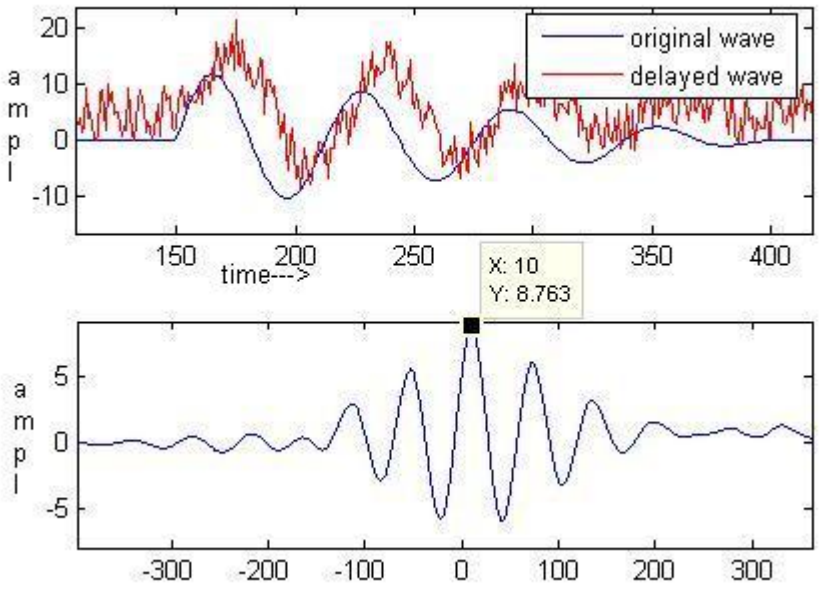


Fig A.12 Normal decay pulse and 10 samples delayed pulse with noise (1 unit) and its cross correlation plot (SNR=8.88, Correlation sequence' peaks ratio 1.44)

The normal sine waves with delay of 10 and 20 samples respectively shown in Fig A.13 and A.14. Note that cross correlation peaks are at 10 and 20 in Fig A.13 and A.14 respectively.

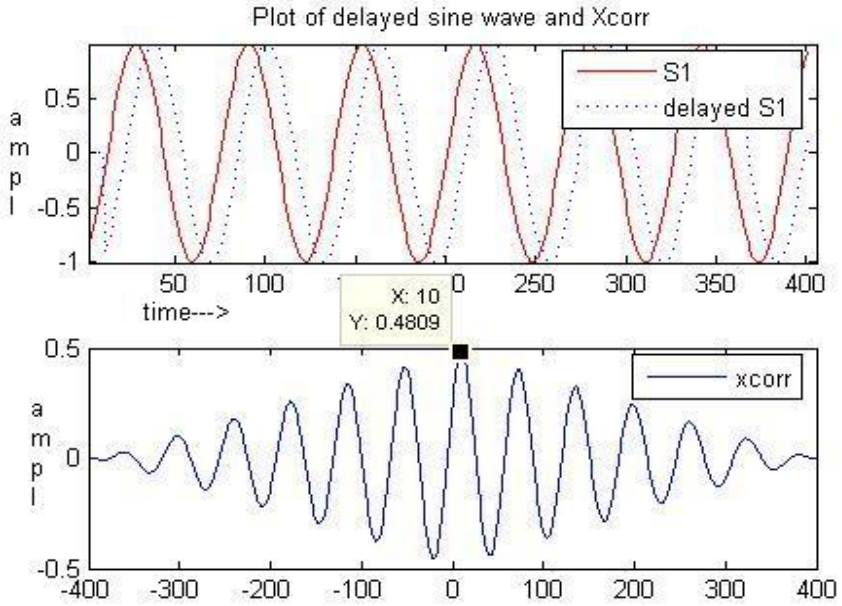


Fig A.13 Normal sine wave & 10 samples delayed sine wave and cross correlation plot (Correlation sequence' peaks ratio 1.19)

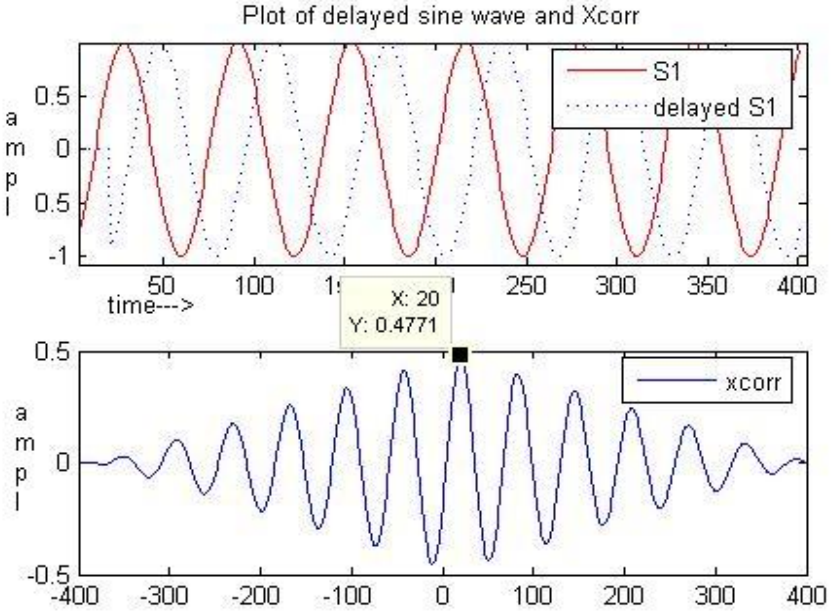


Fig A.14 Normal sine wave & 20 samples delayed sine wave and cross correlation plot (Correlation sequence' peaks ratio 1.18)

Fig A.15 and A.16 shows sine wav and noisy sine wave with 10 samples delay. The noise added was random noise 0.5 unit and 1 unit in delayed sine wave. The location of peaks in the cross correlation are at 10 in Fig A.15 and A.16.

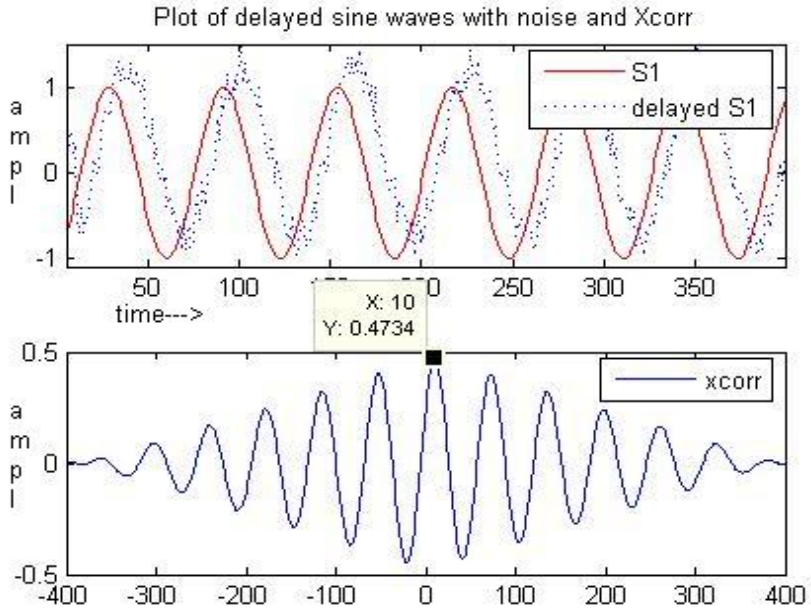


Fig A.15 Normal sine wave and 10 samples delayed sine wave with noise (0.5 unit) and its cross correlation plot (SNR=16.42, Correlation sequence' peaks ratio 1.16)

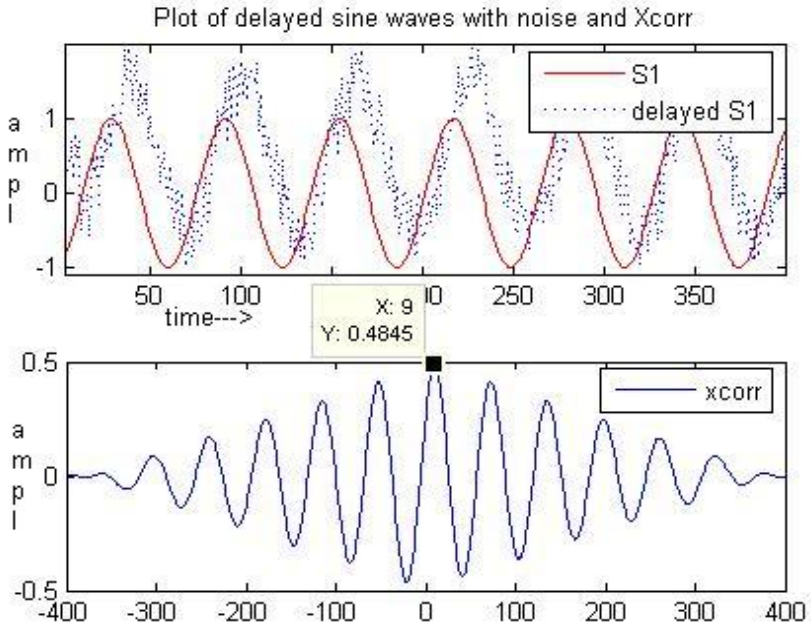


Fig A.16 Normal sine wave and 10 samples delayed sine wave with noise (1 unit) and its cross correlation plot (SNR=6.13, Correlation sequence' peaks ratio 1.18)

Actual recorded waveforms and cross correlation sequence plot

The pulse wave is recorded using flow velocity profiler. Two flow velocity profilers are used to sense the pulse from radial point and brachial point along the same artery. During the recording one of the channel of acquisition unit not working properly so one waveform is little noisy in nature.

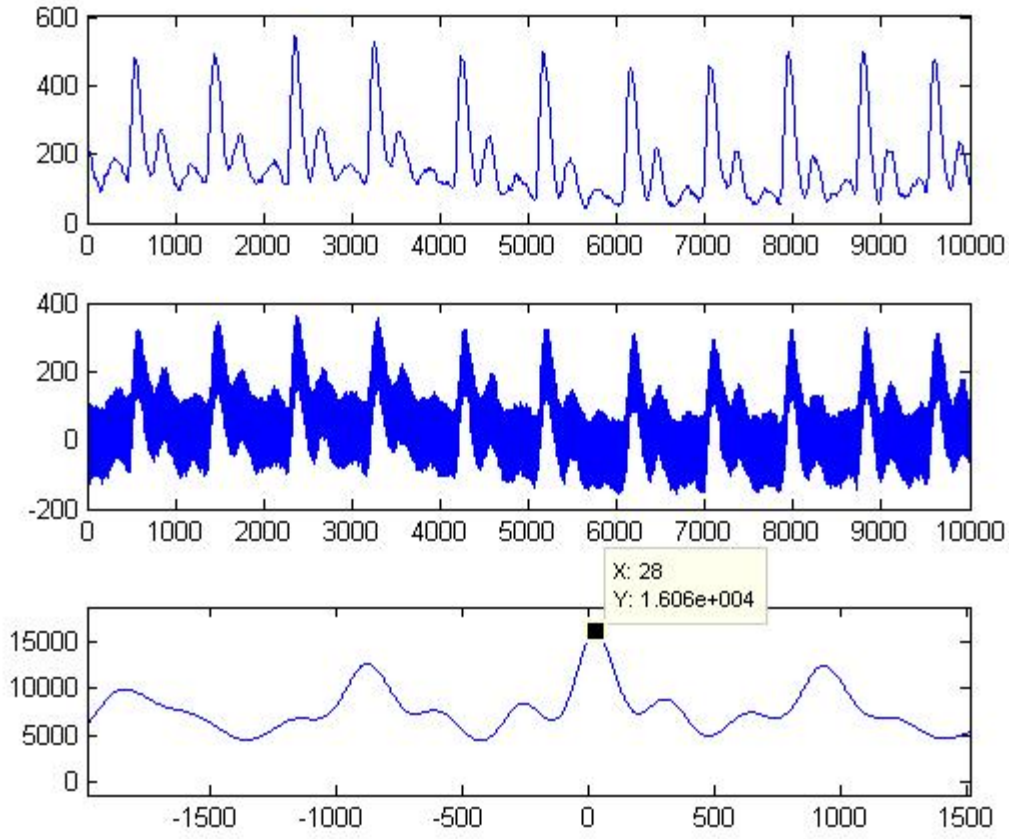


Fig A.17 Pulse waves recorded using velocity profiler and cross correlation plot

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