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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IIT Bombay **Sarika S. Gattawar**

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Abstract

Noninvasive recording of pressure pulse waveform from radial artery can be used for obtaining valuable diagnostic information, by analyzing it for temporal characteristics, spectral characteristics and its cross-correlation with other physiologically related waveforms. In this project, the pulse waveform was obtained by using a piezoelectric transducer. The effect of physical exercise on radial arterial pulse waveform is studied. Spectral analysis of radial arterial pulse waveform has been investigated using five spectral parameters: spectral energy ratio, harmonic distortion, log spectrum mean frequency, standard deviation, and normalized skewness. Further, pulse waveform has been cross-correlated with simultaneously recorded electrocardiogram, phonocardiogram, and photoplethysmogram in order to study the timing relationship between these waveforms. Finally, the correlation coefficients between pairs of these 12 parameters were computed and studied.

Contents

List of symbols

Symbol	Explanation
K	Spring constant
F_1	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

Noninvasive recording of the pressure pulse waveform from the radial artery can be used for obtaining valuable diagnostic information, by analyzing it for temporal characteristics, spectral characteristics, and its cross-correlation with phonocardiogram, photoplethysmogram, and electrocardiogram. In allopathic medicine, 'taking the pulse' is a part of battery of diagnostic procedures, and is often used only for heart rate and variability. But to the physicians practicing *ayurveda*, traditional Tibetian medicine, Unani medicine, and traditional Chinese medicine, etc, a study of patient's pulse is of paramount importance [1].

According to *ayurveda*, by using *nadishastra* technique, one can get information about the three *doshas* in the body: *vata*, *pitta*, and *kapha* [2]. Normally physician's palm supports the patient's wrist and pulse examination is done using three fingers: index, middle, and ring finger on the radial artery [3]. In *ayurvedic* literature, the three fingers are associated with three *doshas*: index finger- *vata*, middle finger- *pitta* and ring finger- *kapha*. Several instruments have been developed and reported for sensing the pulse waveform and giving the output as an electrical analog voltage or as digitized samples and built-in analysis [5][6][7][8][9].

1.2 Objective

This project is in continuation of analysis work done earlier at IIT Bombay as a part of M. Tech. project by Aparna Surve [4]. Her project included study of different types of transducers for sensing, and analyzing the pulse waveform at wrist. She investigated recording of pulse waveform using the transducer of an electronic stethoscope or phonocardiograph. But, the signal was corrupted by noise, environmental sounds as well as the vibrations from various smaller blood vessels,

and poor low frequency response of the sensor. Hence, spectral subtraction method was used for noise reduction in pulse waveform. Cross-correlation of the enhanced pulse waveform with PCG was studied, in order to study timing relationship as an indication of change in arterial blood flow [4].

The objective of this project is to extend the exploratory study for diagnostic information in the radial arterial pulse waveform. Recording of pulse waveform using the piezoelectric transducer has been investigated. Analysis is carried out by simultaneous recording of radial arterial pulse waveform, phonocardiogram, electrocardiogram and photoplethysmogram from subjects with normal health, under rest and exercising condition. Analysis has been carried out for studying the effect of stress on the radial arterial pulse waveform. This has been done by way of spectral analysis of radial arterial pulse, and cross-correlation of the pulse waveform with the other physiologically related waveforms.

1.3 Dissertation outline

In the second chapter of the report, the different sensors used for acquisition of pulse waveform and review of analysis of pulse wave are discussed. Chapter 3 describes the experimental set up used for signal acquisition 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

RADIAL ARTERIAL PULSE WAVEFORM

Several techniques for acquisition and analysis of radial arterial pulse have been reported. Some of these are described here.

2.1 Dudgeon's sphygmograph

In 1882, Dudgeon designed sphygmograph for measuring blood pressure from the radial artery at the wrist as shown in Fig 2.1 [2][3]. The instrument is made of a starter on its upper surface, two pulleys at the two ends of a small rotatory bar, a freely hanging needle and a key which is set in the back of the body of the instrument. The instrument is used for pulse tracing by rotating key in anticlockwise direction. A rectangular piece of smoked paper is fitted in between the two pulleys for pulse wave recording. When the starter is set, pulleys start working by rotating the small bar. Thus the smoked paper is moved forward and pulse tracing is done by means of the hanging needle. Dudgeon's sphygmograph was used by Upadhyay [5] for obtaining pulse tracings and quantitative measurements on there tracing for pulses classified in accordance with *nadishastra*. Fig 2.2 shows some sample pulse tracings.

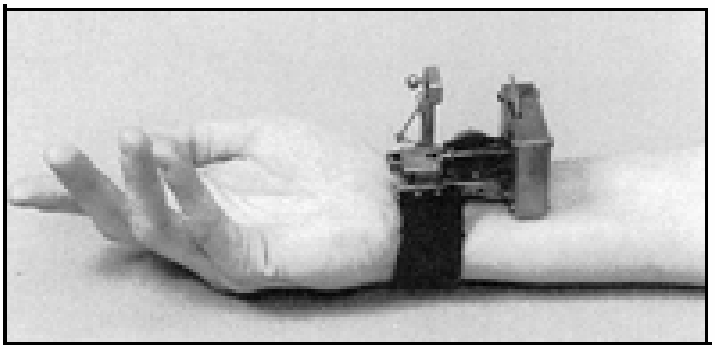

Fig 2.1 Dudgeon's sphygmograph [6]

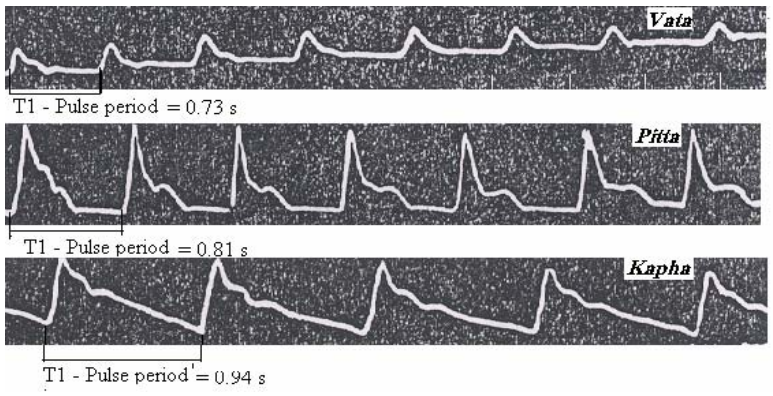

Fig 2.2 Pulse tracings using Dudgeon's sphygmograph as obtained by Upadhyay [5]

2.2 Arterial tonometer

The arterial tonometer is an instrument used for measuring arterial blood pressure (1963). Typically, it is placed over a superficial artery; the radial artery on the wrist is one convenient site for tonometer measurement [7].

Fig 2.3 shows an idealized model for illustration of tonometer working. 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. An ideal membrane transmits only a tensile force T, and does not transmit any bending moment. The tension vector shown, T, is perpendicular to the pressure vector; so the force F, is independent of T, and depends only on the blood pressure and the area of the frictionless piston, A. Thus, measurement of the force F permits one to directly measure the intra-arterial pressure [7].

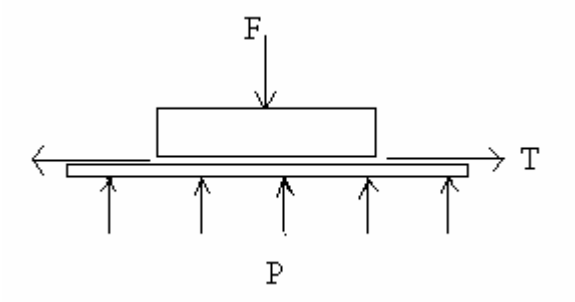

Fig 2.3 Idealized model for a tonometer [7]

The sensor assembly is held by a strap with hold-down force of F_1. The tonometer sensor is modeled as an assembly of springs with spring constant *K*. The arterial rider senses arterial pressure. Side structure allows the sensor to rest on the arterial wall. Design of sensor is based on following assumptions [7].

- The artery above which sensor is placed is supported from below by bone (e.g. the radial artery is supported by radial bone) and the thickness of the skin over the artery is insignificant compared to the diameter of the artery.
- The arterial rider as shown in Fig 2.4 is smaller than the flattened area of the artery, and is placed over the flattened area of artery. It is about 0.2 mm wide.
- The spring constant *K* of the force transducer is large as compared to the effective spring constant of the artery.

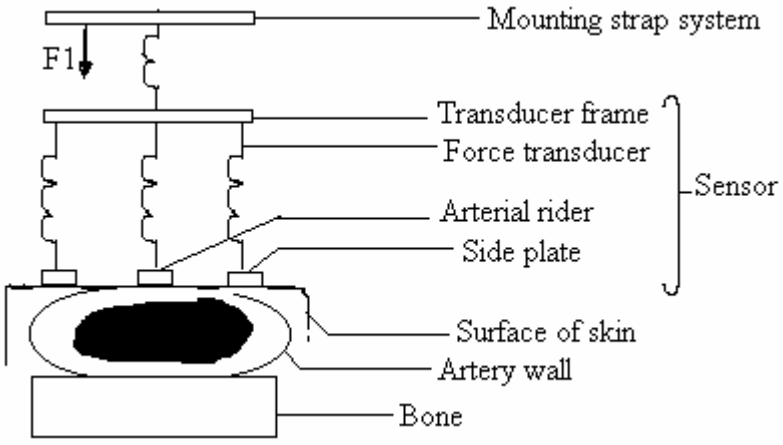

Fig 2.4 Schematic diagram of simple arterial tonometer [7]

Recording of pulse signal is done by adjusting appropriate hold down force F_1. The procedure involves increasing the hold-down force and simultaneously pulse signal is recorded as shown in Fig 2.5. The pulse amplitude slowly increases as shown in part A, becomes maximum as shown in part B, and further reduces in part C, irrespective of any increase in F_1. Hence F_1 used for acquisition of pulse signal as shown in part B, is selected as optimum hold-down force. The tonometer sensor uses strain gage transducer, semiconductor pressure transducer, or a capacitive transducer [7].

An arterial rider present in simple tonometer requires accurate placement over the superficial artery, hence requires a skilled operator. A multiple-element arterial tonometer sensor [7] is shown in Fig 2.6. It consists of an array of minimum 25

arterial riders with inter-element spacing of about 0.2 mm [7]. The sensor requires precise positioning over the artery such that some elements of the array are centered

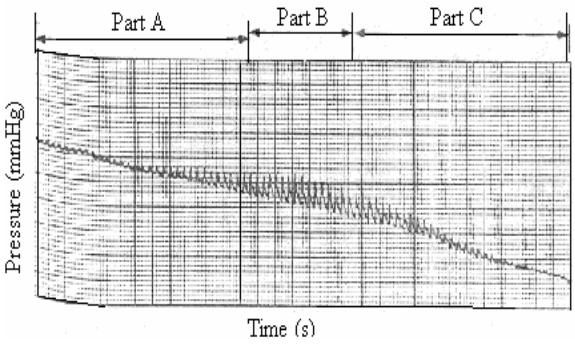

Fig 2.5 Procedure for obtaining optimal hold-down force in simple tonometer [7]

over the artery. Then a computer automatically selects the sensor element that is correctly positioned over the artery for acquisition of pulse pressure. It searches for the largest pulse amplitude, the corresponding sensor element will then be chosen for further acquisition. Multiple-element tonometer sensor uses piezoresistive strain gages attached to diaphragm of 10 μm thick [7]. Some of the sensors based on arterial tonometry principle are described here.

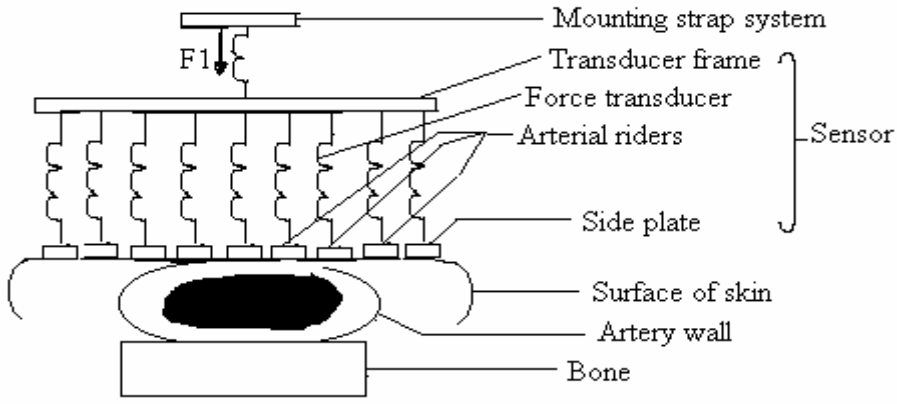

Fig 2.6 Schematic diagram of multiple-element arterial tonometer [7]

"Model 7000", product of Colin Medical Instruments Corp. [10], works on this principle. It provides the beat-to-beat blood pressure values with arterial pressure waveform along with numeric values for systolic, mean, diastolic pressures, as well as pulse rate using piezoelectric pressure transducers. Fig. 2.7 shows the sensor position on the wrist and Fig 2.8 shows its working. This sensor contains array of piezoelectric pressure transducers separated by 0.2 mm [10]. The sensor is placed on the wrist over

the radial artery. A pneumatic pump and bellows press the transducer array against the skin and tissue above an artery. This pressure is known as the hold-down pressure. To determine optimal hold- down pressure, the monitor searches through a range of pressure values until it measures the largest pulse pressure value, the procedure is as shown in Fig 2.9. When the artery is partially flattened, a graph called tonogram can be plotted to show the pulse amplitude versus transducer number. The sensor element whose pulse amplitude is near the maximum pulse amplitude is calibrated to the systolic and diastolic values obtained in the oscillometric cuff measurement and used for pulse acquisition [10].

Fig 2.7 Sensor position used in Model 7000 [10]

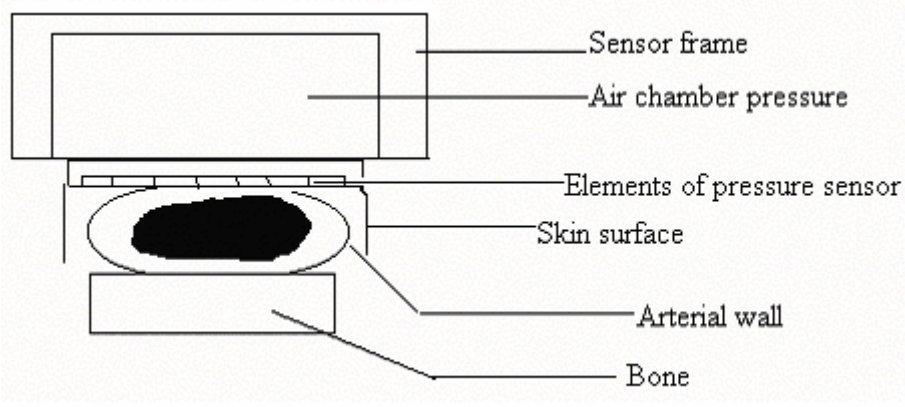

Fig 2.8 Sensor used in Model 7000 [10]

"MediWatch", recently reported device is based on the principle of tonometry. It is a non-invasive, continuous, multi-purpose device designed to monitor the blood pressure and pulse rate. It has a medical pressure sensor housed in a special casing, which contains a plunger that is 'free-floating' as it applanates the radial artery as shown in Fig. 2.10. The strap is specially designed to provide a constant force for effective applanation and ensuring the position of the sensor housing to remain constant after any wrist movements as shown in Fig. 2.11. The change in the electrical signals due to change in pressure is detected as a result of the piezoresistive nature of the sensor are then sent to the watch head via three small cables along the strap.

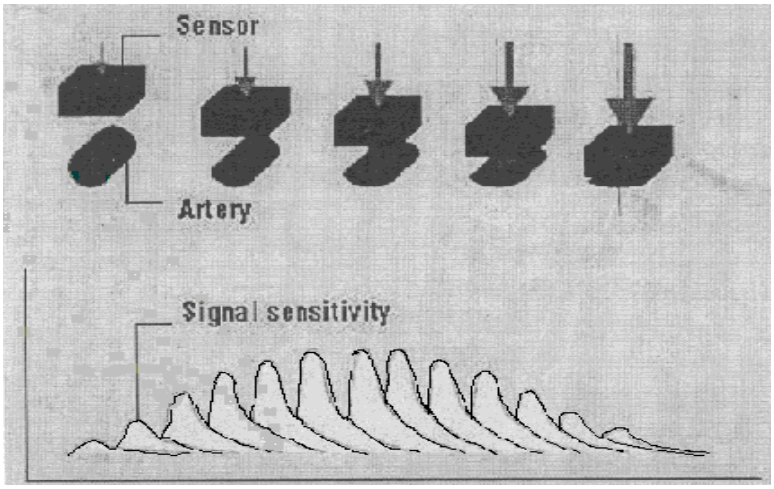

Fig 2.9 Procedure for obtaining optimal hold-down pressure in Model 7000 [10]

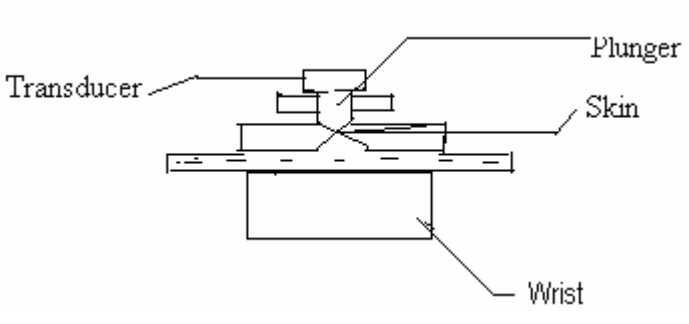

Fig 2.10 Pulse sensor "MediWatch" [9]

Fig 2.11 Top view of MediWatch [9]

This device has a LCD display panel to read the real-time blood pressure and heart rate. It is also able to transfer the data to the computer using standard RS232 format or Wireless Technology. MediWatch provides continuous, beat-to-beat wrist

arterial pulse rate measurements. It takes continuous reading of the Systolic and Diastolic blood pressure (Range: 10 - 300 mmHg.) and has the capacity to store four weeks' worth of data. Fig. 2.12 shows the radial arterial pulse waveform obtained by MediWatch.

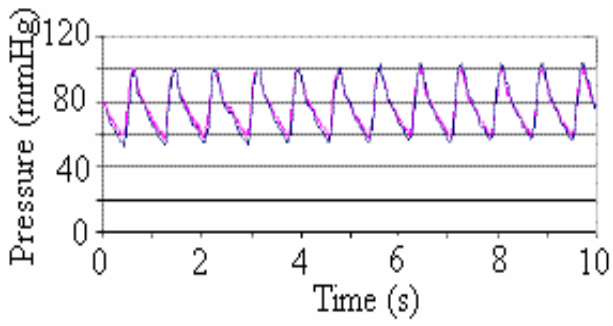

Fig 2.12 Pulse waveform obtained by MediWatch [9]

2.3 Microphone based system

Binghe and Jinglin [11] have reported a microphone based system in 1998 for detecting pulse signal from the radial artery, which is as shown in Fig 2.13. It is composed of the sound-coupling cavity, condenser microphone (B&K- 4147), preamplifier (B&K- 2639), microphone power supply (B&K- 2804) and the data recorder. The condenser microphone was used as a transducer to convert pulse on the wrist into electrical signals. The pulse wave radiating from the skin at the radial artery is transmitted trough the coupling cavity onto the diaphragm of the microphone and emerged as electrical signals, which are then digitized for further analysis. The power spectra of four different types of pulses: normal pulse, smooth pulse, wiry pulse and slow-intermittent pulse, obtained by using the microphone based system are as shown in Fig 2.14.

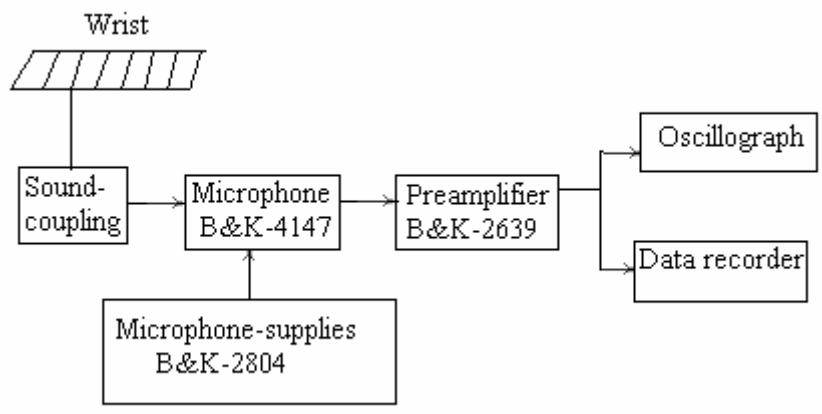

Fig 2.13 Microphone based pulse sensing system for pulse signal,

reported by Binghe and Jinglin [11]

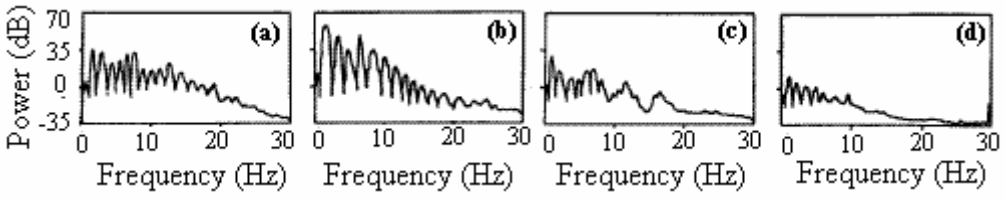

Fig 2.14 Power spectra of pulse signals (a) normal pulse (b) smooth pulse (c) wiry pulse (d) slow-intermittent pulse [11]

2.4 Multichannel radial pulse wave transducer

Recently in 2000 new measuring system is suggested and developed, which enables the three points measurement to simulate the manual diagnosis. This technique is based on tonometry principle. The system is composed of four pressure vessels, pressure sensors, and air applying pumps [12]. Out of the four pressure vessels, one is used for appropriately pressing the radial artery and three of them for detecting pressure change in several mmHg levels. The pneumatic system used in this system is based on Pascal law. This pneumatic system works under two major assumptions:

(a) A tissue is assumed as a fluid as the Poisons ratio of the tissue is relatively high (0.2~0.4).

(b) According to the Pascal law, the pressure distribution under the transducer and the rider is uniform, so the pressure distribution is also uniform along with the artery.

Systolic-Diastolic Pressure (SDP) curve method evaluated the performance of the pneumatic system. The continuous pressure regulation system composed of a solenoid valve, pump, and cavity is controlled by pulse width modulation (PWM) signal. Fig 2.15 shows the transducers designed for three-point measurement.

As the depressing pressure goes up, the flow of blood in artery gets disturbed and blood pressure rises up. This pressure changes can be monitored by differential pressure sensor. The SDP curve verifies whether an artery is properly flattened or not. If an artery is flattened properly, then there exists a point where systolic and diastolic pressure curves meet [12]. Fig 2.16 shows the pressure curve obtained at three positions, and point D denotes the pressure at which artery is completely flattened. The distance between the systolic and the diastolic pressure curve is the amplitude of a pulse wave. Fig 2.17 shows the pulse waveform obtained at depressing pressure of 96 mmHg.

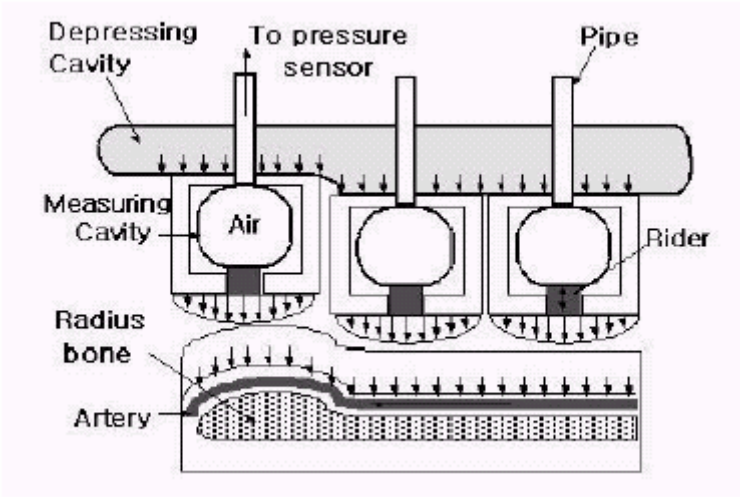

Fig 2.15 Transducers for three-point measurement [12]

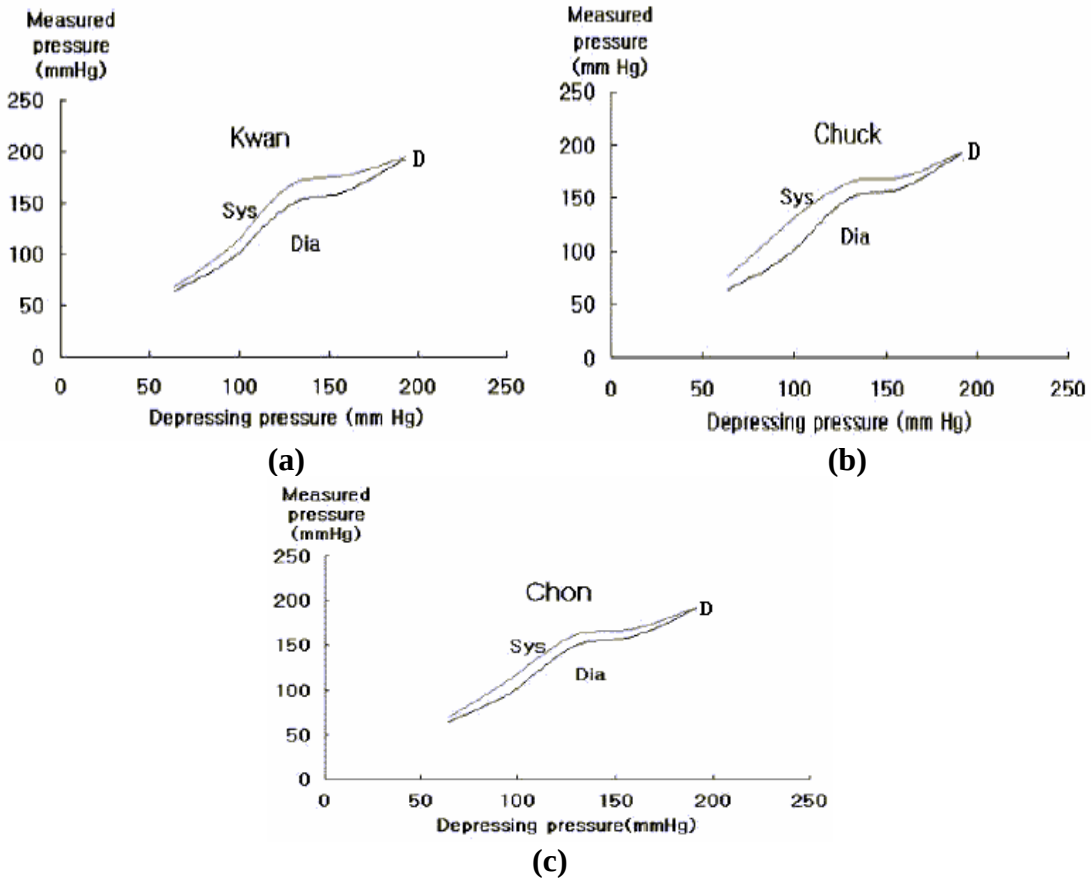

Fig 2.16 **(a)** Pressure waveform obtained at *Kwan*
(b) Pressure waveform obtained at *Chuck*
(c) Pressure waveform obtained at *Chon* [12]

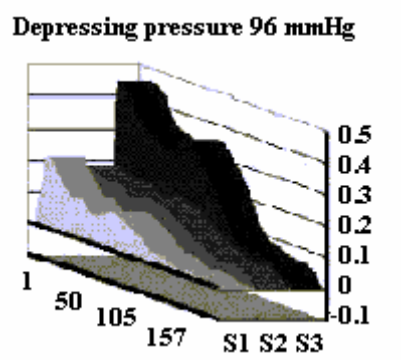

Fig 2.17 Pulse wave at depressing pressure 96mmHg [12]

2.5 Acquisition using phonocardiograph sensor and piezoelectric transducer

In 2003, at IIT Bombay an electronic stethoscope or phonocardiograph, which is normally used for recording of the heart sounds and murmurs, was used for pulse acquisition. The PCG and pulse waveform were acquired by using two different electronic stethoscopes, "Medetron" and "Stethmate". Both are made of air-coupled crystal microphone. The crystal microphones contain a wafer of piezoelectric material, which generates an electrical output when subjected to mechanical stresses due to heart sounds. They are smaller in size and more sensitive [4]. But, the diameter of the chest-piece (1.5") of phonocardiograph is comparatively larger than the diameter of the radial artery. Hence along with the pulse signal, the noise: environmental sounds and the vibrations from various smaller blood vessels were picked up. In addition, the poor low frequency response of the sensor resulted in severe waveshape disorders. It was concluded that acquisition was adequate only for studying timing relationship with other waveforms but not for studying the shape of the pulse waveform itself.

Further a piezoelectric transducer (diameter = 0.5") was used for pulse pick up. It generates an electrical output when subjected to mechanical stresses due to the vibrations at the radial artery, and this electrical output is recorded. The transducer is 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. 2.18 shows the pulse waveform recorded using phonocardiograph sensor and piezoelectric transducer [4].

(a) Pulse using phonocardiograph sensor

(b) Pulse using piezoelectric transducer

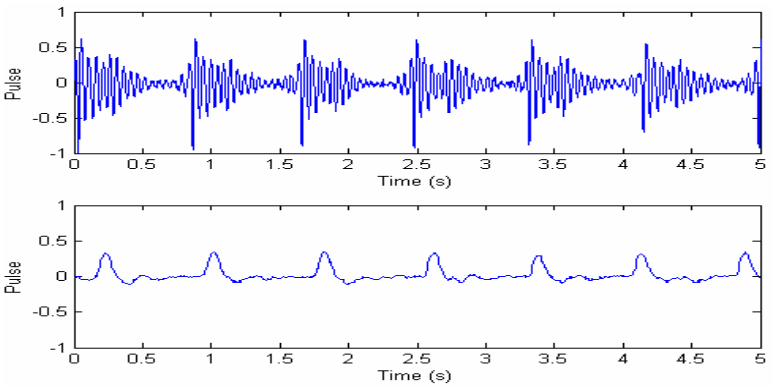

Fig 2.18 Pulse recorded using phonocardiograph sensor and piezoelectric transducer [4]

2.6 Analysis of pulse waveform

Upadhyay [5] used Dudgeon's sphygmograph for pulse sensing and quantitative measurements. The analysis of pulse waveform involved study of following parameters [5].

- 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 top points of the wave. It is due to rate of contraction of left ventricle.
- Angle of deviation of percussion wave.
- Distance of dicrotic notch from the base line.

According to *ayurveda*, by using *nadishastra* technique, one can get information about the three *doshas*: *vata*, *pitta* and *kapha* in the body [2][3]. Upadhyay studied the above parameters for pulse waves with the pulses classified in accordance with the three *doshas*. Fig 2.20a, Fig 2.20b and Fig 2.20c shows the sample pulse wave obtained from normal subjects with *vata*, *pitta* and *kapha dosha* respectively.

From the Fig.2.20, 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.

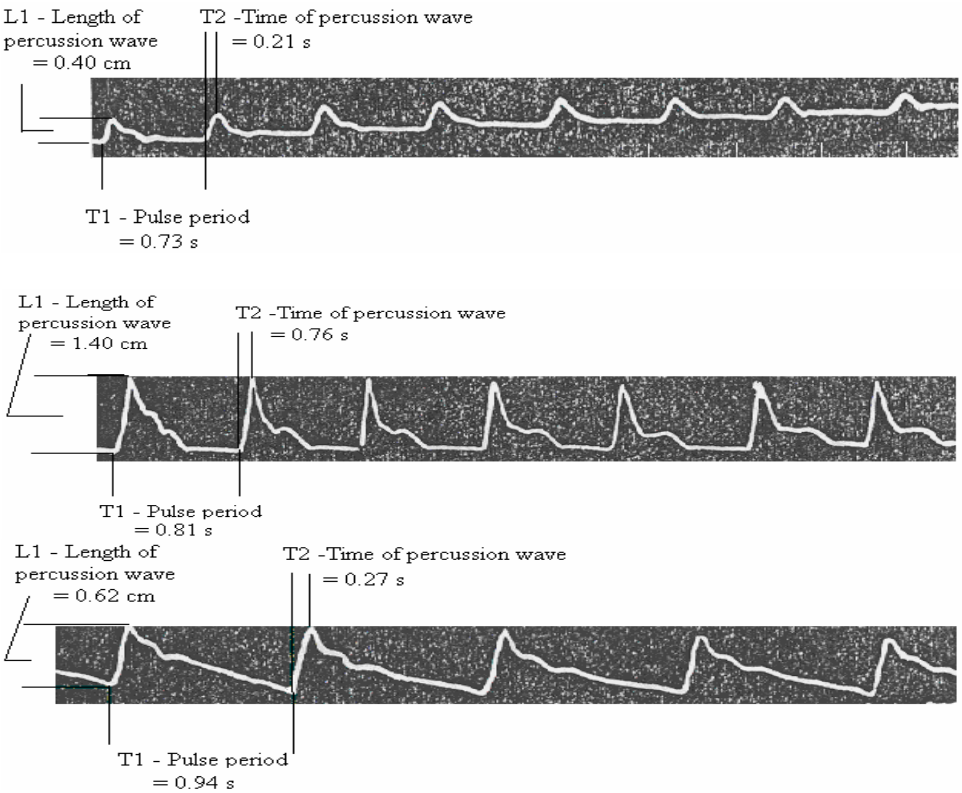

Fig 2.19 (a) *Vata* Pulse, **(b)** *Pitta* Pulse, and **(c)** *Kapha* Pulse obtained using Dudgeon's sphygmograph [5]

Dasrao et al [8] 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 2.21. Based on these parameters, the arterial system of subject was described which involved following indices [8].

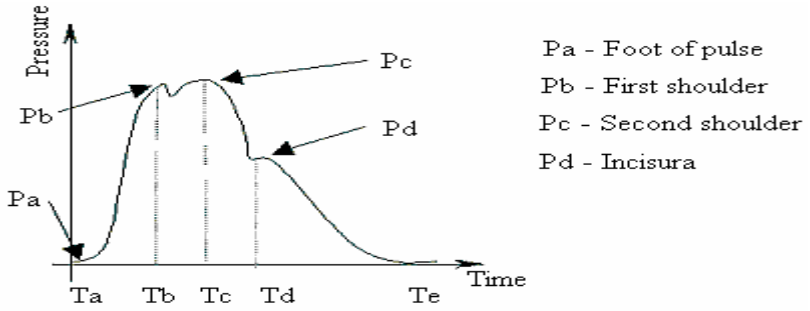

Fig 2.20 Pulse wave analysis using MediWatch [8]

- Augmented pressure is defined as the pressure difference between the first peak, P_b and second peak, P_c.
- Systolic (tension) pressure time index is the integral of pressure multiplied by time throughout systole.
- Diastolic pressure time index is the integral of the diastolic part of the pressure wave.
- Sub-endocardial viability ratio is the ratio of diastolic pressure time index to systolic pressure time index.
- Pulse pressure is the pressure difference between the systolic pressure P_c and end-diastolic pressure P_a.
- Mean arterial pressure is the area under curve of a whole pulse wave cycle divided by time period of cycle.

$$MAP(mmHg) = \frac{\sum_{j=T_a}^{T_e} P_j}{T} \qquad (2.6.1)$$

where T = time period of pulse wave (T_e - T_a)

- Mean systolic pressure is the average pressure between the foot of pulse, P_a and incisura, P_d.

$$MSP(mmHg) = \frac{\sum_{j=T_a}^{T_d} P_j}{T_d - T_a} \qquad (2.6.2)$$

- Mean diastolic pressure is the average pressure between the incisura, P_d and beginning of next pulse wave.

$$MDP(mmHg) = \frac{\sum_{j=Td}^{T_e} P_j}{T_e - T_d} \qquad (2.6.3)$$

Binghe and Jinglin [11] 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 [11]. The pulse signal was low pass filtered with cut-off frequency 50 Hz. 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) as shown in Fig 2.22.

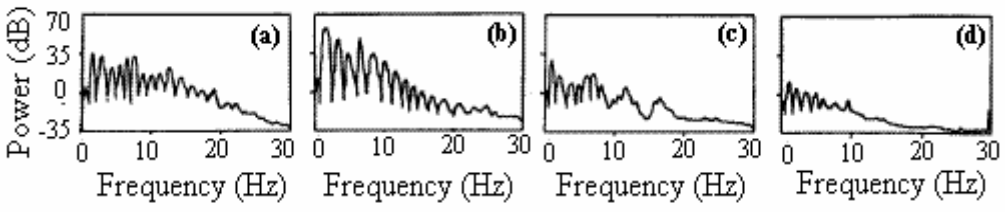

Fig 2.21 Power spectra of pulse signals **(a)** normal pulse **(b)** smooth pulse **(c)** wiry pulse **(d)** slow-intermittent pulse [11]

Power spectra show that spectral density extends up to 25 Hz, with the envelope decreasing with increase in frequency. The spectral energy of pulse is approximately concentrated below about 10 Hz. Hence the spectral energy within 10 Hz, and the total energy was obtained by integrating the energy over 0 Hz-10 Hz and 0 Hz-40 Hz respectively. 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.

Aparna Surve [4] 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 2.24 shows the cross-correlation of PCG with RAP.

(a) Cross-correlation at 120 bpm

(b) Cross-correlation at 90 bpm

(c) Cross-correlation at 66 bpm

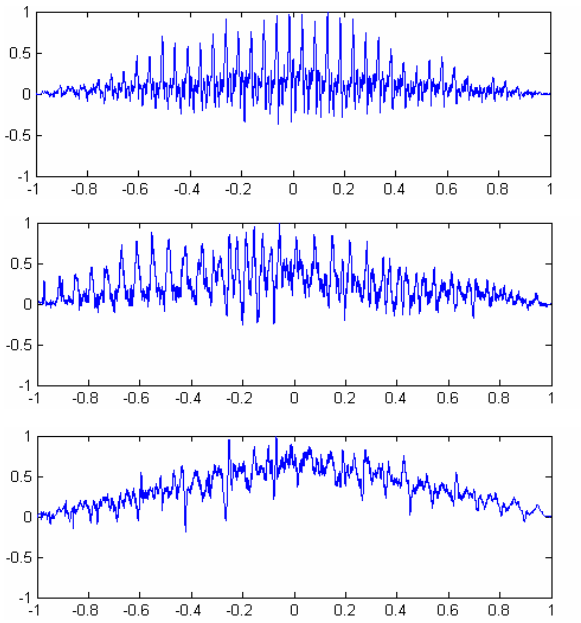

Fig 2.22 Cross-correlation between PCG and pulse recorded using piezoelectric transducer at different times during post-exercise relaxation on a subject with normal health [4]

Chapter 3
SIGNAL ACQUISITION AND ANALYSIS

3.1 Introduction

The objective of this project is to carry out an exploratory analysis of radial arterial pulse (RAP) waveform for diagnostic information. For this purpose signal acquisition, display and analysis has been carried out on a PC. The spectral characteristics of the waveform and its time relationship with other physiologically related waveforms have been investigated.

This chapter provides a description of the signal acquisition setup and signal analysis, and the results from the analysis are presented and discussed in the following chapter.

3.2 Signal acquisition

The pulse waveform was acquired by using a piezoelectric transducer. It generates an electrical output when subjected to mechanical stresses due to the vibrations at the radial artery, and this electrical output is recorded [13]. The transducer is kept in place over radial artery by closing the velcro strap firmly around the wrist. Positioning is adjusted in order to get the optimal signal strength.

Along with RAP waveform, three other physiologically related waveforms were simultaneously recorded. These are the electrocardiogram (ECG), phonocardiogram (PCG), and finger tip photoplethysmogram (PPG).

An electrocardiogram is a recording of the changes occurring in the electrical potential difference between different sites on the skin as a result of cardiac activity [14]. Obtaining electrocardiogram involves the specific electrode placement, and site preparation for reducing the amount of impedance between the electrode and the skin surface. For ECG recording, 3 electrodes were used for right arm, left arm, and left leg using stainless steel clamp electrodes. Electrode gel was applied to the electrode in order to increase its conductive contact with the skin, and hence the output voltage.

Signals were recorded using an ECG amplifier (SECG, from Pamtrons, Mumbai) from lead II (potential difference between left arm and right arm), selected on the basis of strongest QRS complex for normal subjects [14] [15].

The activity of cardiac valves gives rise to sounds that can be sensed from the chest by using a stethoscope or phonocardiograph. The recording of these sounds known as phonocardiogram (PPG) [16]. The recording sensor has inverted conical shape in order to pick up vibrations with high intensity. Position of the sensor was adjusted on the chest wall for maximum pick up. For recording, a phonocardiograph (SPCG 01, Pamtrons, Mumbai) was used.

Photoplethysmogram is non-invasively obtained electro-optical signal widely used in monitoring the pulsation associated with change in blood volume in the peripheral vascular bed [17]. Transmission and reflection are the two different ways of measurement in PPG. Here we have used reflection mode of measurement using index finger of the left hand for signal recording. The reflected light, which reaches the photo-detector, causes variation in photo-detector current, which is assumed to be related to blood volume changes underneath the probe [17]. For PPG recoding, circuit developed in our lab by Vinod Pandey was used [18].

After adjusting the positions for all the four sensors for acquiring optimum strength of signals, simultaneous recording of the four signals was done. Spectral analysis of these waveforms showed that RAP, ECG, PCG, and PPG extended up to 450, 680, 700, 500 Hz respectively. Recordings were done without using antialiasing filters. Hence a sampling rate of 1 kSa/s was considered as appropriate. Further it was found that use of 10 bits did not result in loss of any significant waveform features and hence 12 bit ADC resolution is sufficient for signal acquisition. Hence the four waveforms were simultaneous acquired using 12-bit resolution at 1 kSa/s. the signal acquisition was done using USB based data acquisition unit (Adlink USBDAQ-9100-MS). Signals were recorded in blocks of 5 k samples (20 k samples for all the 4 channels) i.e. 5 s records. Fig. 3.1 shows an example of simultaneously recorded pulse waveform along with ECG, PCG and PPG wave, when subject was at rest.

The recordings were obtained on 5 male volunteer subjects (24-28 years); with no known health problems. On each subject, recording was made under full rest condition. 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. This was carried out to study the relation between heart rate (HR) and

the four waveforms at different values of HR. Blood pressure was recorded under rest condition and immediately after the exercise. It was taken again after the last recordings in the relaxation phase. Recordings during exercise phase itself were not taken to avoid motion artifacts. From each subject, the recordings were taken on 5 days within a week (as per the convenience of volunteer subject).

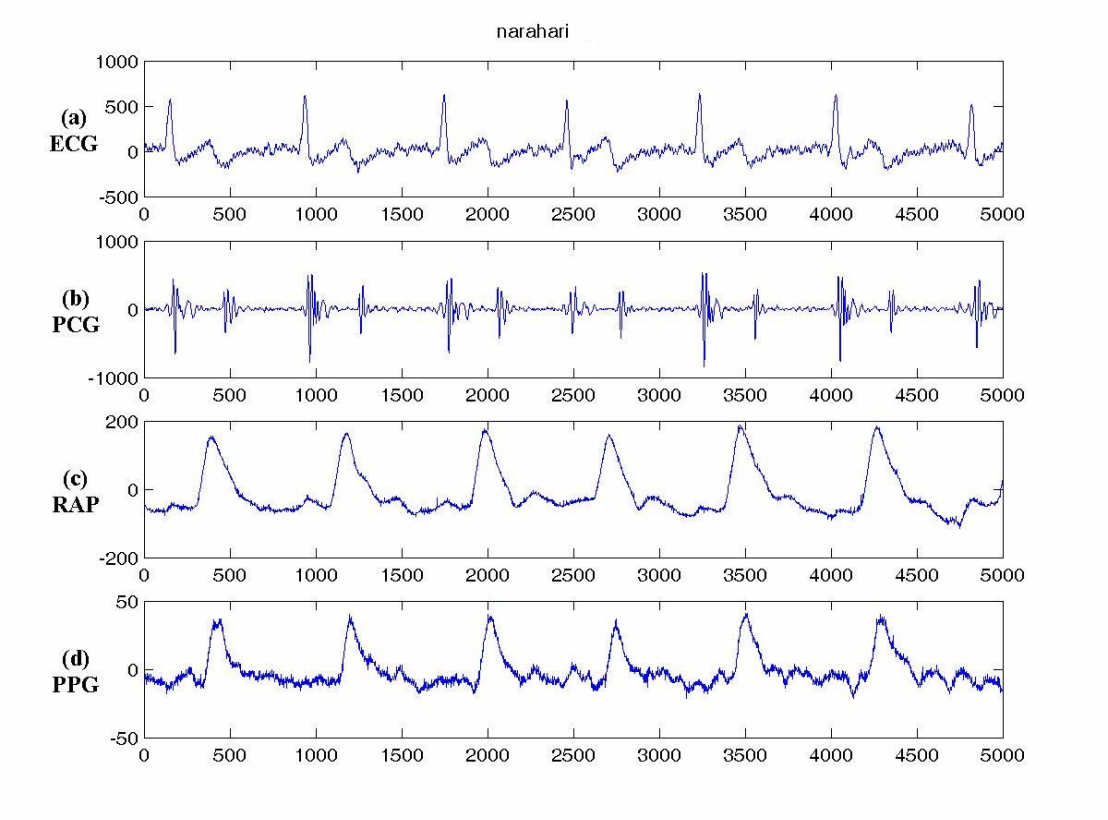

Fig 3.1 (a) ECG, **(b)** PCG, (**c)** RAP, and **(d)** PPG wave of subject S2_Nar. Wave amplitudes are in arbitrary units.

3.3 Spectral analysis

Analysis of RAP waveform has been carried out for measurements in time domain [5] [8] as well as in frequency domain [11]. Time domain measurements on the waveshape are sensitive to the phase response of the sensor. Frequency domain measurements on the power spectrum of the signal are not affected by the phase response and hence are likely to be more robust. Hence it was decided to make measurements related to the shape of the power spectrum. In an earlier study [11], it has been reported that RAP spectrum generally extends only up to 40 Hz, and that a factor called “spectral energy ratio”, or SER, defined as the ratio of the energy below

10 Hz to the total energy, is related to different types of pulses. We have decided to use this factor. In order to quantify the distribution of energy in the harmonics, we have used total harmonic distortion. Additionally in order to quantify the shape of the log power spectrum, we have obtained the mean frequency, standard deviation, normalized skewness.

The power spectrum of RAP waveform was obtained using averaging of the squared magnitude spectrum obtained from DFT of windowed segments of 5 k sample record. Larger window length gives better spectral resolution, while averaging of windows over a larger record length decreases statistical variations [19]. It was found that spectrum did not change appreciably for windows longer than 2.7 k samples, i.e. approximately 3 cardiac beats. For averaged power spectra, 2.7 k sample windows were used with 75% overlap.

With 5000-point DFT (2.7 k samples padded with zero valued samples), we get the averaged magnitude spectrum $|X(k)|$, for $0 \le k \le 2499$. For sampling rate f_s = 1 k Sa/s, the frequency indices corresponding to 10 Hz and 40 Hz are 50 and 200 respectively. Equations for the various analysis parameters discussed above are as the following:

$$\text{Spectral energy ratio (SER)} = \frac{\sum_{k=0}^{k=49} |X(k)|^2}{\sum_{k=0}^{k=199} |X(k)|^2} \tag{3.1}$$

$$\text{Harmonic distortion (HD)} = \sqrt{\frac{\sum_{k=p}^{k=199} |X(k)|^2}{\sum_{k=1}^{k=p-1} |X(k)|^2}} \tag{3.2}$$

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

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

$$S_d(k) = 10 \log |X(k)|^2 \tag{3.3}$$

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

$$\bar{k} = \left| \frac{\sum_{k=0}^{199} k\, S_d(k)}{\sum_{k=0}^{199} S_d(k)} \right| \tag{3.4}$$

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

$$\sigma_k = \sqrt{\frac{\sum_{k=0}^{199} (k-\bar{k})^2\, S_d(k)}{\sum_{k=0}^{199} S_d(k)}} \tag{3.5}$$

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

$$\text{Mean } \bar{f} = \bar{k}\, f_s/5000 \tag{3.6}$$

$$\text{S.D. } \sigma_f = \sigma_k\, f_s/5000 \tag{3.7}$$

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

$$\text{NSK} = \frac{1}{\sigma_k} \sqrt{\frac{\sum_{k=0}^{199} (k-\bar{k})^3\, S_d(k)}{\sum_{k=0}^{199} S_d(k)}} \tag{3.8}$$

3.4 Cross-correlation with physiologically related waveforms

The objective in computing correlation between the two signals is to measure the degree to which the two signals are similar. The cross-correlation between two signal sequences $x(n)$ and $y(n)$ is a sequence $r_{xy}(l)$, which is defined as [20]

$$r_{xy}(l) = \sum_{n=-\infty}^{\infty} x(n) y(n-l) \qquad l = 0, \pm 1, \pm 2, \ldots \tag{3.9}$$

or, equivalently, as

$$r_{xy}(l) = \sum_{n=-\infty}^{\infty} x(n+l) y(n) \qquad l = 0, \pm 1, \pm 2, \ldots \tag{3.10}$$

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 [20]. Hence the location of the peak in the cross-correlation of two physiologically related waveforms may give the propagation delay.

For our study ECG, PCG, RAP, and PPG, all physiologically related to cardiac cycle, were simultaneously recorded. Pairs of these waveforms were cross-correlated: ECG-PCG, ECG-RAP, ECG-PPG, PCG-RAP, PCG-PPG, and RAP-PPG. The location of peak in cross correlation of ECG and PCG waveform is an indication of delay between electrical activity of the heart and mechanical opening of the valves. Similarly considering ECG as reference signal, its cross correlation with RAP waveform gives an indication of delay between contraction of left ventricle in aorta and pressure pulse at radial artery. The delay in pressure pulse at radial artery also depends on compliance of artery, and blood flow rate. Hence the ECG-RAP values may give an indication of state of arteries.

In order to get base values of the delays, recordings with subjects at rest were used. To investigate the effects of changes in beat rate and blood flow on these delays, recordings taken during the post-exercise relation have been used. Simultaneously recorded ECG, PCG, RAP, and PPG waveforms a subject at rest are earlier shown in Fig. 3.1. Cross-correlation for different pairs of these waveforms is shown in Fig. 3.2.

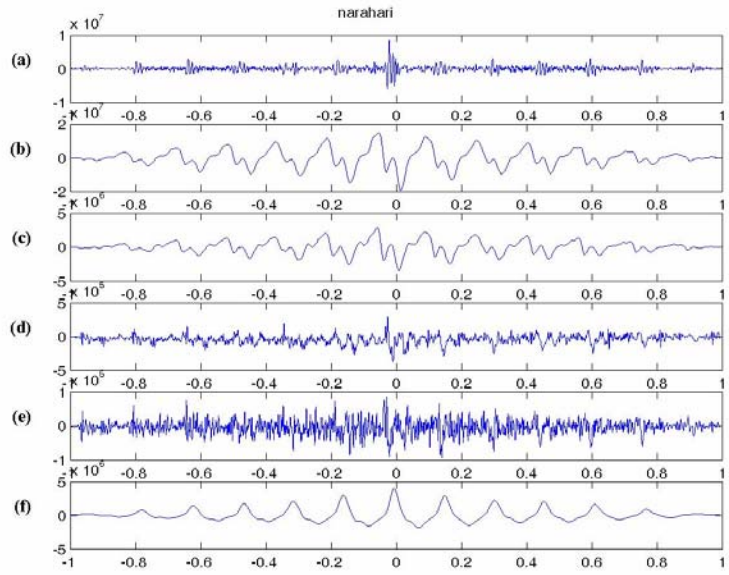

Fig 3.3 (a) ECG-PCG, **(b)** ECG-RAP, (**c)** ECG-PPG**, (d)** PCG-RAP, **(e)** PCG-PPG , **(f)** RAP-PPG cross-correlated wave of subject S2_Nar.

It has been observed that in the ECG along with QRS complex, which indicates ventricular contraction, P and T waves have prominent amplitude. In the PCG signal two heart sounds are perceived. Closure of tricuspid and mitral valves generates first heart sound, whereas activity of aortic and pulmonary valves corresponds to second heart sound. In case of RAP and PPG only one prominent amplitude peak is there which corresponds to the arterial pressure and volumetric change in blood flow respectively. Due to the presence of multiple peak complexes in ECG and PCG, there was ambiguity in locating maximum peak in cross correlation. Hence it was decided to carry out pre-processing on ECG and PCG waveforms to enhance one of the peak complexes, in order to get accurate estimate of delays in these physiologically related waveforms. For our study we have separated the first and second heart sound in PCG waveform, and cross-correlation has been obtained with the first heart sound only. This is being an exploratory study, cross-correlation with pre-processed ECG were not carried out at this stage.

For separating heart sounds, energy envelope of PCG was calculated and then by threshold detection, first and second heart sounds were separated by using a software developed earlier by Vinod Pandey [18] [21]. As shown in Fig. 3.3, first PCG signal is passed through a band pass filter to attenuate high and low frequency noise and physiological interferences. Further squaring is done and squared waveform is low pass filtered to get energy envelope.

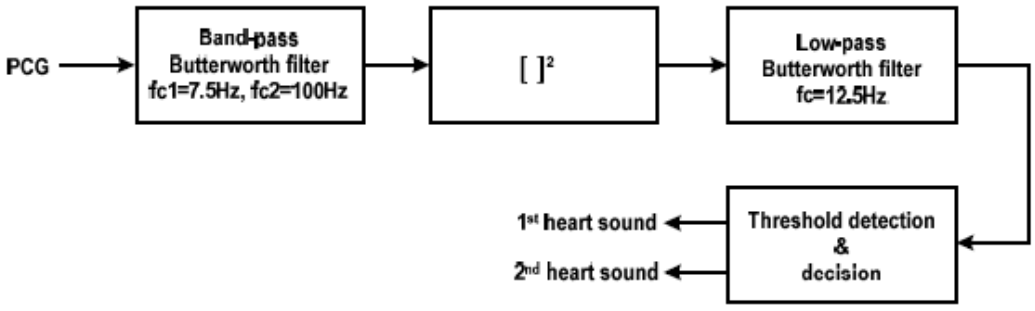

Fig 3.3 Processing stages for separating first and second heart sound [18] [21]

Threshold detection is done on energy envelope by applying window, and size of window was selected to include one heart sound only. By threshold detection, peaks within the window size of 300 ms are located. Further window is advanced to check threshold crossing and to find next peak of energy envelope. After threshold detection by decision process first and second heart sound is identified. In the decision process

the index of detected peaks are compared with previous peak. If the time difference between i^{th} peak and $(i-1)^{th}$ peak is greater than i^{th} and $(i+1)^{th}$ peak, than $(i- 1)^{th}$ peak is identified as second heart sound and i^{th} peak as first heart sound. After separating first and second heart sounds, cross-correlation of first heart sound with RAP, and PPG is used to find the delay. Cross-correlation for different pairs of waveforms with First heart sound is shown in Fig. 3.4. In this figure cross-correlation of first heart sound with respect to RAP as well as PPG gives very clearly defined peaks, as seen in plots (d) and (e) respectively, compared to very noisy plots in Fig. 3.3

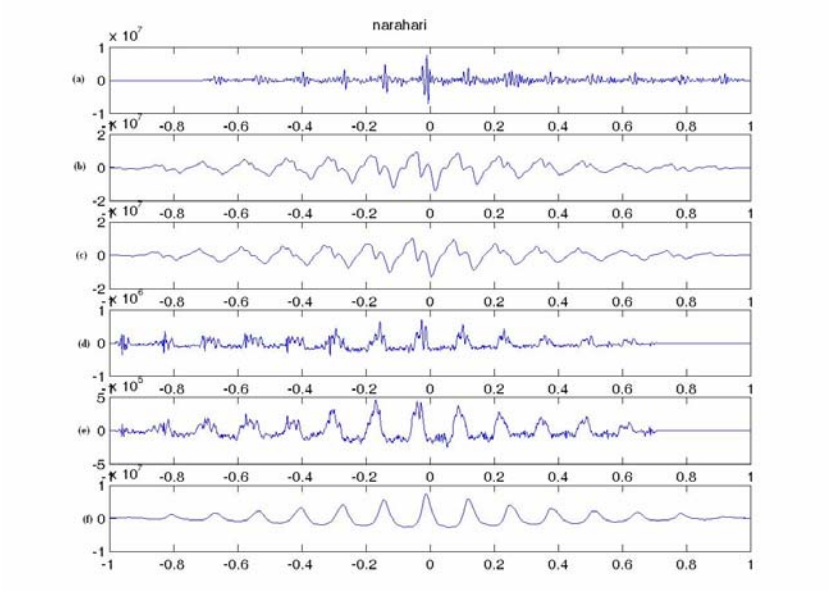

Fig 3.4 (a) ECG-I^{st} PCG, **(b)** ECG-RAP, (**c)** ECG-PPG**, (d)** I^{st} PCG-RAP, **(e)** I^{st} PCG-PPG , **(f)** RAP-PPG cross-correlated wave of subject S2_Nar.

Chapter 4
RESULTS AND DISCUSSION

4.1 Introduction

The recordings were obtained from 5 male volunteer subjects (age: 24-28 years, given in Table 4.1) with normal health and no known cardiac disorders. The recording was first taken under rest condition. Subsequently, the subject exercised on an exercise bicycle, so that the pulse rate increased. The subject was advised to select the pace and level of exercise such that it was vigorous but not uncomfortable. During the post exercise relaxation, recordings were taken at regular intervals of approximately 5 minutes, until the rate returned to near rest condition. In each recording session, the blood pressure was also recorded: at rest, immediately after the exercise, and at the end of the last recording. These recordings were taken once everyday for 5 days, spread over a week. The time of the recording on different days and across the subjects varied (as per the convenience of the volunteer subjects), and hence we can not use these recordings for any relationship with the time of the day, activity level, time elapsed after meals.

4.2 Analysis

Investigations involved following analyses:

(a) Heart rate (HR) and blood pressure (BP) variations

(b) Spectral analysis of RAP waveform, by using the 5 spectral parameters: spectral energy ratio (SER), harmonic distortion (HD), log spectrum mean frequency (SMF), standard deviation (SDF), and normalized skewness (NSK), as given in Section 3.3.

(c) Location of peaks in the cross-correlation of pairs of the ECG, PCG, RAP, and PPG waveforms, as described in Section 3.4.

Statistical analysis of heart rate (HR), and the above parameters, in the form of mean and standard deviation across the various recording conditions, was tabulated. Further, the correlation coefficients [22] [23] between pairs of these 12 parameters were computed and tabulated.

4.3 Results

Table 4.1 gives the average HR and BP for the subjects.

Table 4.1 Subjects' information

Subject code	S1-Bha	S2_Nar	S3_Nav	S4_Sach	S5_Mer
Age (years)	24	24	24	28	24
Avg. HR (bpm)	80	83	90	99	80
Avg. Systolic BP (mmHg)	104	110	114	158	123
Avg. Diastolic BP (mmHg)	73	70	78	112	82

Table 4.2 gives the HR and RAP spectral parameters at resting condition (pre-exercise) across the days for each subject. Table 4.3 - 4.7 give the same values under various test condition, subjectwize. The results are plotted in Fig. 4.1 a-e.

Table 4.8 gives the delays between waveform pairs obtained from location of cross-correlation peaks, under resting condition (pre-exercise). Values under various phases of post-exercise relaxation are tabulated in Table 4.9 - 4.13, subjectwize. The results are plotted in Fig. 4.2 a – e.

In this study we have used a total of 12 parameters: HR, 5 RAP spectral parameters, and 6 delays between waveform pairs. Without any apriori hypothesis about relation between parameters, they were correlated in pairs, by treating each recording as a trial. Thus for each subject we had 25 recordings (5 days $\times$ 5 recordings/day). For a $\alpha f = 23$, a correlation >0.5 will indicate strong correlation. Table 4.14 gives the values of correlation between these parameters, when subjects are at resting condition (pre-exercise). Table 4.15 to 4.19 gives the same values under various test condition, subjectwize.

Table 4.2 Pre-Exercise HR and RAP spectral parameters of all the subjects

Sub	Day	BP		HR	ER	HD	Mean	Std. Dev	NSK
		(mmHg)		(bpm)			(Hz)		
S1	1	107	67	80	99.6	59.7	17.5	11.9	6.5
	2	94	64	83	99.9	44.9	16.9	11.7	6.9
	3	100	78	78	99.9	76.2	16.9	11.7	6.9
	4	111	76	96	98.6	66.7	17.4	11.6	6.3
	5	107	79	65	99.6	69.6	17.5	11.9	6.5
	Mean	104	73	80	99.5	63.4	17.2	11.8	6.6
	Std. Dev.	7	7	11	0.6	11.9	0.3	0.1	0.3
S2	1	120	67	98	99.4	27.1	17.9	11.8	5.9
	2	112	67	85	97.8	78.5	17.3	11.5	6.8
	3	94	63	76	99.1	60.7	17.2	11.7	6.8
	4	118	81	91	99.9	73.0	16.9	11.7	6.9
	5	105	70	83	98.6	104.0	17.2	11.5	6.9
	Mean	110	70	87	98.9	68.7	17.3	11.6	6.7
	Std. Dev.	11	7	8	0.8	28.1	0.4	0.1	0.4
S3	1	133	82	123	99.3	45.2	17.8	11.9	6.3
	2	113	73	80	97.8	94.9	17.3	11.5	6.8
	3	96	68	73	99.8	185.4	16.5	11.6	7.4
	4	109	74	93	99.7	78.7	17.3	11.8	6.8
	5	117	93	83	99.4	80.1	17.5	11.8	6.6
	Mean	114	78	90	99.2	96.9	17.3	11.7	6.8
	Std. Dev.	13	10	20	0.8	52.7	0.5	0.2	0.4
S4	1	156	120	106	99.9	42.4	16.4	11.6	7.5
	2	151	106	106	99.9	29.6	17.1	11.9	6.9
	3	171	109	93	99.8	52.8	16.9	11.6	6.2
	4	161	117	87	99.9	20.6	17.0	11.7	6.9
	5	152	106	101	99.2	57.7	17.9	11.9	6.1
	Mean	158	112	99	99.7	40.6	17.0	11.8	6.7
	Std. Dev.	8	7	8	0.3	15.5	0.5	0.1	0.6
S5	1	118	78	75	99.9	42.7	16.8	11.7	7.1
	2	118	79	81	99.9	65.7	16.6	11.6	7.3
	3	125	83	83	99.9	66.3	16.8	11.8	7.2
	4	140	87	78	99.2	74.3	17.5	11.8	6.5
	5	113	83	85	99.8	99.5	16.9	11.8	6.9
	Mean	123	82	80	99.7	69.7	16.9	11.8	7.0
	Std. Dev.	11	4	4	0.3	20.4	0.3	0.1	0.3
Total	**Mean**	122	83	87	99.4	67.8	17.2	11.7	6.8
	Std. Dev.	22	17	13	0.6	32.6	0.4	0.1	0.4

Table 4.3 HR and RAP spectral parameters of subject S1_Bha

Day	Condition	BP	HR	ER	HD	Mean	Std. Dev.	NSK
		(mmHg)	(bpm)			(Hz)		
1	Pre-Ex	107/67	80	99.6	59.7	17.5	11.9	6.5
	Str-1	126/72	100	99.3	29.7	18.4	12.0	5.6
	Str-2	.	95	99.5	35.6	18.2	11.9	5.5
	Str-3		84	99.5	49.5	17.9	11.9	5.9
	Str-4	101/75	84	99.7	40.4	18.2	11.9	5.7
	Mean		89	99.6	42.9	18.0	11.9	5.8
	Std. Dev.		9	0.1	11.8	0.4	0.0	0.4
2	Pre-Ex	94/64	83	99.9	44.9	16.9	11.7	6.9
	Str-1	121/72	103	99.9	14.1	17.4	11.9	6.6
	Str-2		99	99.9	8.0	17.4	11.9	6.6
	Str-3		84	98.9	47.2	17.5	11.7	6.6
	Str-4	99/67	85	98.8	79.2	17.5	11.8	6.7
	Mean		91	99.5	38.7	17.3	11.8	6.7
	Std. Dev.		9	0.6	28.7	0.3	0.1	0.1
3	Pre-Ex	100/78	78	99.9	76.2	16.9	11.7	6.9
	Str-1	119/76	142	99.1	43.0	17.5	11.8	6.4
	Str-2		101	98.9	55.8	17.5	11.7	6.6
	Str-3		96	99.2	50.2	17.4	11.6	6.5
	Str-4	104/70	96	99.5	61.5	17.4	11.6	6.8
	Mean		103	99.3	57.4	17.4	11.7	6.7
	Std. Dev.		24	0.4	12.6	0.2	0.1	0.2
4	Pre-Ex	111/76	96	98.6	66.7	17.4	11.6	6.3
	Str-1	112/70	103	99.7	64.9	17.2	11.7	6.8
	Str-2		98	99.9	45.8	17.4	11.9	6.6
	Str-3		89	98.1	71.1	17.3	11.6	6.8
	Str-4	108/67	87	98.8	63.9	17.1	11.4	7.0
	Mean		95	98.9	62.5	17.3	11.6	6.7
	Std. Dev.		7	0.8	9.7	0.1	0.2	0.3
5	Pre-Ex	107/79	65	99.6	69.6	17.5	11.9	6.5
	Str-1	102/65	91	99.5	53.4	17.2	11.8	7
	Str-2		89	99.6	58.6	17.0	11.7	6.9
	Str-3		82	99.7	80.3	17.4	11.9	6.7
	Str-4	118/59	75	99.7	83.9	17.4	11.7	6.6
	Mean		80	99.6	69.2	17.3	11.8	6.8
	Std. Dev.		11	0.1	13.2	0.2	0.1	0.2
Total	**Mean**		91	99.4	54.1	17.5	11.8	6.5
	Std. Dev.		14	0.5	19.3	0.4	0.2	0.4

Table 4.4 HR and RAP spectral parameters of subject S2_Nar

Day	Condition	BP	HR	ER	HD	Mean	Std. Dev.	NSK
		(mmHg)	(bpm)			(Hz)		
1	Pre-Ex	120/67	98	99.4	27.1	17.9	11.8	5.9
	Str-1	160/83	128	98.7	68.6	17.6	11.6	6.5
	Str-2		100	98.0	99.2	17.3	11.5	6.7
	Str-3		88	99.1	77.3	17.5	11.8	6.5
	Str-4	120/76	109	99.3	50.9	17.9	11.9	6.0
	Mean		105	98.9	64.6	17.7	11.7	6.3
	Std. Dev.		15	0.6	27.2	0.3	0.2	0.3
2	Pre-Ex	112/67	85	97.8	78.5	17.3	11.5	6.8
	Str-1	170/83	116	98.8	23.4	17.5	11.5	6.6
	Str-2		103	98.7	50.0	17.3	11.3	6.9
	Str-3		90	99.2	84.6	17.6	11.7	6.5
	Str-4	113/73	87	98.3	75	17.3	11.6	6.8
	Mean		96	98.6	62.3	17.4	11.5	6.7
	Std. Dev.		13	0.6	25.4	0.1	0.2	0.2
3	Pre-Ex	94/63	76	99.2	60.7	17.2	11.7	6.8
	Str-1	186/169	137	99.0	45.1	17.3	11.5	6.6
	Str-2		93	98.3	65.9	17.1	11.5	6.9
	Str-3		86	99.6	30.7	17.7	11.9	6.4
	Str-4	127/74	96	98.9	77.6	17.4	11.6	6.6
	Mean		98	98.9	55.9	17.4	11.6	6.7
	Std. Dev.		23	0.5	18.4	0.2	0.2	0.2
4	Pre-Ex	118/81	91	99.9	73.0	16.9	11.7	6.9
	Str-1	164/74	137	99.4	69.3	17.4	11.7	6.6
	Str-2		98	99.3	73.1	17.1	11.5	6.9
	Str-3		84	98.9	80.2	17.1	11.6	6.9
	Str-4	112/94	87	98.5	90.1	17.0	11.5	7.1
	Mean		99	99.2	77.1	17.1	11.6	6.9
	Std. Dev.		22	0.5	8.2	0.1	0.1	0.2
5	Pre-Ex	105/70	83	98.6	104.0	17.2	11.5	6.9
	Str-1	130/72	120	97.3	64.3	17.7	11.6	6.3
	Str-2		98	98.9	92.9	17.3	11.5	6.9
	Str-3		90	99.7	88.1	17.2	11.7	6.8
	Str-4	112/75	95	99.4	68.5	17.2	11.7	6.8
	Mean		97	98.8	83.6	17.3	11.6	6.7
	Std. Dev.		14	0.9	16.8	0.2	0.1	0.3
Total	**Mean**		99	98.9	68.7	17.4	11.6	6.7
	Std. Dev.		17	0.6	21.3	0.3	0.1	0.3

Table 4.5 HR and RAP spectral parameters of subject S3_Nav

Day	Condition	BP	HR	ER	HD	Mean	Std. Dev.	NSK
		(mmHg)	(bpm)			(Hz)		
1	Pre-Ex	133/82	123	99.4	45.2	17.8	11.9	6.3
	Str-1	139/89	160	98.3	32.1	17.7	11.8	6.5
	Str-2		123	99.4	46.2	17.6	11.8	6.4
	Str-3		120	98.8	48.9	17.8	11.8	6.4
	Str-4	116/82	128	99.1	54.7	17.7	11.7	6.5
	Mean		131	98.9	45.4	17.7	11.8	6.4
	Std. Dev.		167	0.6	8.3	0.1	0.1	0.1
2	Pre-Ex	113/73	80	97.8	94.9	17.3	11.5	6.8
	Str-1	135/80	160	98.4	57	17.5	11.6	6.6
	Str-2		128	99.6	79.2	17.4	11.7	6.7
	Str-3		122	99.3	89.1	17.7	11.8	6.4
	Str-4	115/76	109	99.7	63.8	17.0	11.7	6.9
	Mean		120	98.9	76.8	17.4	11.7	6.7
	Std. Dev.		29	0.8	16.2	0.3	0.1	0.2
3	Pre-Ex	96/68	73	99.8	185.3	16.5	11.6	7.4
	Str-1	186/169	132	99.6	61.8	16.9	11.6	7.1
	Str-2		123	99.5	74.8	17.1	11.7	7.0
	Str-3		120	99.8	65.8	17.2	11.7	6.9
	Str-4	127/74	96	99.6	124.8	17.1	11.6	6.8
	Mean		109	99.7	102.5	16.9	11.6	7.0
	Std. Dev.		24	0.1	52.7	0.3	0.1	0.3
4	Pre-Ex	109/74	93	99.7	78.7	17.3	11.8	6.8
	Str-1	134/79	160	99.4	75.7	17.6	11.7	6.6
	Str-2		109	99.2	54.12	17.6	11.7	6.5
	Str-3		129	99.7	76.7	17.2	11.8	6.8
	Str-4	104/74	116	99.6	63.5	17.5	11.9	6.7
	Mean		121	99.5	69.8	17.4	11.8	6.7
	Std. Dev.		25	0.2	10.6	0.2	0.1	0.2
5	Pre-Ex	117/93	83	99.4	80.1	17.5	11.8	6.6
	Str-1	127/72	137	99.1	70.2	17.3	11.6	6.8
	Str-2		101	98.2	91.9	17.3	11.6	6.8
	Str-3		110	99.4	79.8	17.0	11.5	6.9
	Str-4	113/81	106	99.4	87.9	17.1	11.7	7.1
	Mean		107	99.1	82.0	17.2	11.6	6.8
	Std. Dev.		20	0.5	8.4	0.2	0.1	0.2
Total	**Mean**		118	99.2	75.3	17.3	11.7	6.7
	Std. Dev.		23	0.5	30.1	0.3	0.1	0.3

Table 4.6 HR and RAP spectral parameters of subject S4_Sach

Day	Condition	BP	HR	ER	HD	Mean	Std. Dev.	NSK
		(mmHg)	(bpm)			(Hz)		
1	Pre-Ex	156/120	106	99.9	42.4	16.4	11.6	7.5
	Str-1	177/134	191	99.8	23.3	16.9	11.7	6.9
	Str-2		128	99.9	26.5	17.5	11.8	6.6
	Str-3		119	99.7	60.2	16.9	11.6	6.8
	Str-4	164/119	109	99.8	50.7	17.1	11.6	6.9
	Mean		131	99.8	40.6	16.9	11.7	6.9
	Std. Dev.		35	0.1	15.7	0.4	0.1	0.3
2	Pre-Ex	151/106	106	99.9	29.5	17.1	11.9	6.9
	Str-1	159/145	109	99.8	25.7	16.9	11.7	6.9
	Str-2		109	99.3	57.2	17.5	11.7	6.41
	Str-3		122	99.7	30.3	16.9	11.6	7.1
	Str-4	151/120	112	99.8	82.6	17.3	11.8	6.7
	Mean		112	99.7	45.1	17.2	11.7	6.8
	Std. Dev.		6	0.2	24.4	0.3	0.1	0.3
3	Pre-Ex	171/109	93	99.8	52.8	16.6	11.6	6.2
	Str-1	177/111	128	99.5	72.7	17.1	11.6	6.9
	Str-2		120	99.4	49.3	17.5	11.8	6.5
	Str-3		120	99.7	59.4	17.4	11.8	6.6
	Str-4	152/113	116	99.5	77.8	17.2	11.7	6.8
	Mean		115	99.6	62.4	17.2	11.7	6.6
	Std. Dev.		13	0.2	12.4	0.2	0.1	0.3
4	Pre-Ex	161/117	87	99.9	20.6	17.0	11.7	6.9
	Str-1	187/169	147	99.4	59.3	17.6	11.7	6.4
	Str-2		116	99.6	76.4	17.5	11.7	6.5
	Str-3		111	99.4	61.7	17.4	11.7	6.8
	Str-4	159/119	106	99.8	71.6	17.3	11.7	6.7
	Mean		113	99.6	57.9	17.4	11.7	6.6
	Std. Dev.		22	0.2	21.9	0.2	0.0	0.2
5	Pre-Ex	152/106	101	99.2	57.7	17.9	11.9	6.1
	Str-1	224/206	153	99.4	71.1	16.9	11.4	7.2
	Str-2		112	99.8	92.0	16.8	11.7	7.2
	Str-3		108	99.8	74.4	17.1	11.8	6.9
	Str-4	158/106	101	99.3	72.1	17.2	11.7	6.8
	Mean		115	99.5	73.5	17.2	11.7	6.8
	Std. Dev.		22	0.3	12.3	0.5	0.2	0.5
Total	**Mean**		117	99.6	55.9	17.2	11.7	6.8
	Std. Dev.		21	0.2	20.5	0.3	0.1	0.3

Table 4.7 HR and RAP spectral parameters of subject S5_Mer

Day	Condition	BP	HR	ER	HD	Mean	Std. Dev.	NSK
		(mmHg)	(bpm)			(Hz)		
1	Pre-Ex	118/78	75	99.9	42.7	16.8	11.7	7.1
	Str-1	151/136	121	99.7	68.3	16.9	11.6	7.0
	Str-2		93	99.7	74.7	16.7	11.6	7.3
	Str-3		90	99.6	58.7	16.6	11.6	7.3
	Str-4	120/79	89	99.9	57.6	16.7	11.8	7.1
	Mean		94	99.8	60.4	16.8	11.7	7.2
	Std. Dev.		17	0.1	12.2	0.2	0.1	0.1
2	Pre-Ex	118/79	81	99.9	65.7	16.6	11.6	7.3
	Str-1	145/86	108	99.9	58.9	16.9	11.7	7.1
	Str-2		103	99.7	89.9	17.0	11.7	7.0
	Str-3		96	99.8	64.5	17.1	11.8	6.9
	Str-4	113/81	101	99.9	87.6	17.1	11.8	6.9
	Mean		98	99.8	73.3	16.9	11.7	7.0
	Std. Dev.		10	0.1	14.4	0.2	0.1	0.2
3	Pre-Ex	125/83	83	99.9	66.3	16.8	11.8	7.2
	Str-1	173/156	123	99.8	88.3	17.0	11.8	7.1
	Str-2	119/82	101	99.8	94.9	17.2	11.9	6.9
	Str-3		100	99.9	54.6	16.2	11.6	7.6
	Str-4	126/86	96	99.9	89.6	16.6	11.7	7.4
	Mean		101	99.9	78.7	16.8	11.8	7.2
	Std. Dev.		14	0.1	17.4	0.4	0.1	0.3
4	Pre-Ex	140/87	78	99.2	74.3	17.5	11.8	6.5
	Str-1	133/79	96	99.6	99.9	16.9	11.7	7.0
	Str-2		91	99.8	74.6	16.9	11.7	6.9
	Str-3		96	99.9	69.6	17.2	11.8	6.7
	Str-4	123/90	101	99.5	88.3	17.1	11.7	6.9
	Mean		92	99.6	81.3	17.1	11.8	6.8
	Std. Dev.		9	0.26	12.5	0.2	0.1	0.2
5	Pre-Ex	113/83	85	99.8	99.5	16.9	11.8	6.9
	Str-1	125/77	103	99.8	91.4	16.8	11.9	7.4
	Str-2		98	99.7	99.8	17.1	11.8	6.9
	Str-3		98	99.7	87.9	17.3	11.9	6.7
	Str-4	122/81	96	99.8	99.5	17.2	11.9	6.9
	Mean		96	99.8	95.6	17.1	11.9	6.9
	Std. Dev.		7	0.1	5.6	0.2	0.1	0.2
Total	**Mean**		96	99.8	77.9	16.9	11.8	7.0
	Std. Dev.		11	0.2	16.7	0.3	0.1	0.2

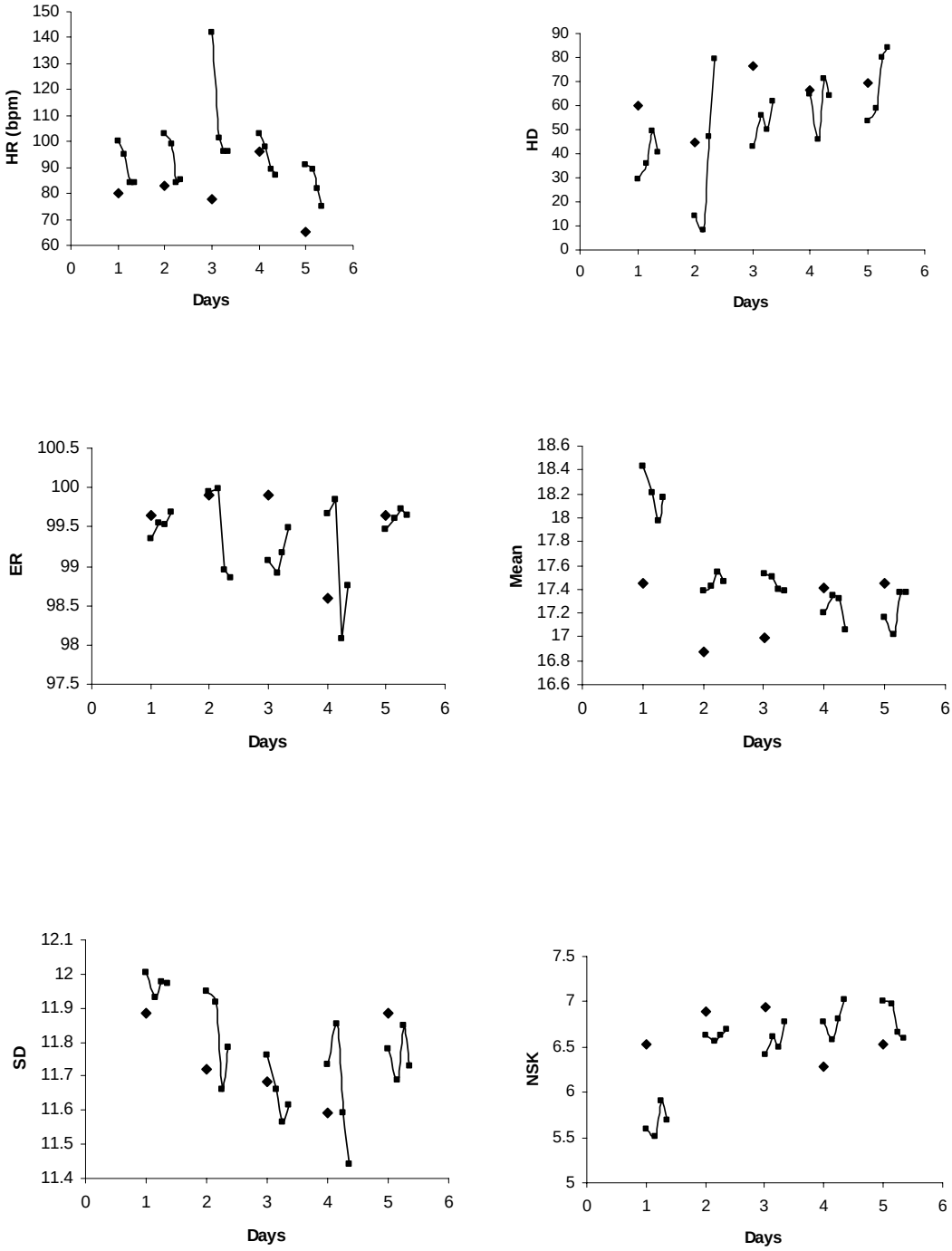

Fig. 4.1 (a) Plot of HR and RAP spectral parameters with exercise. Subject: S1_Bha

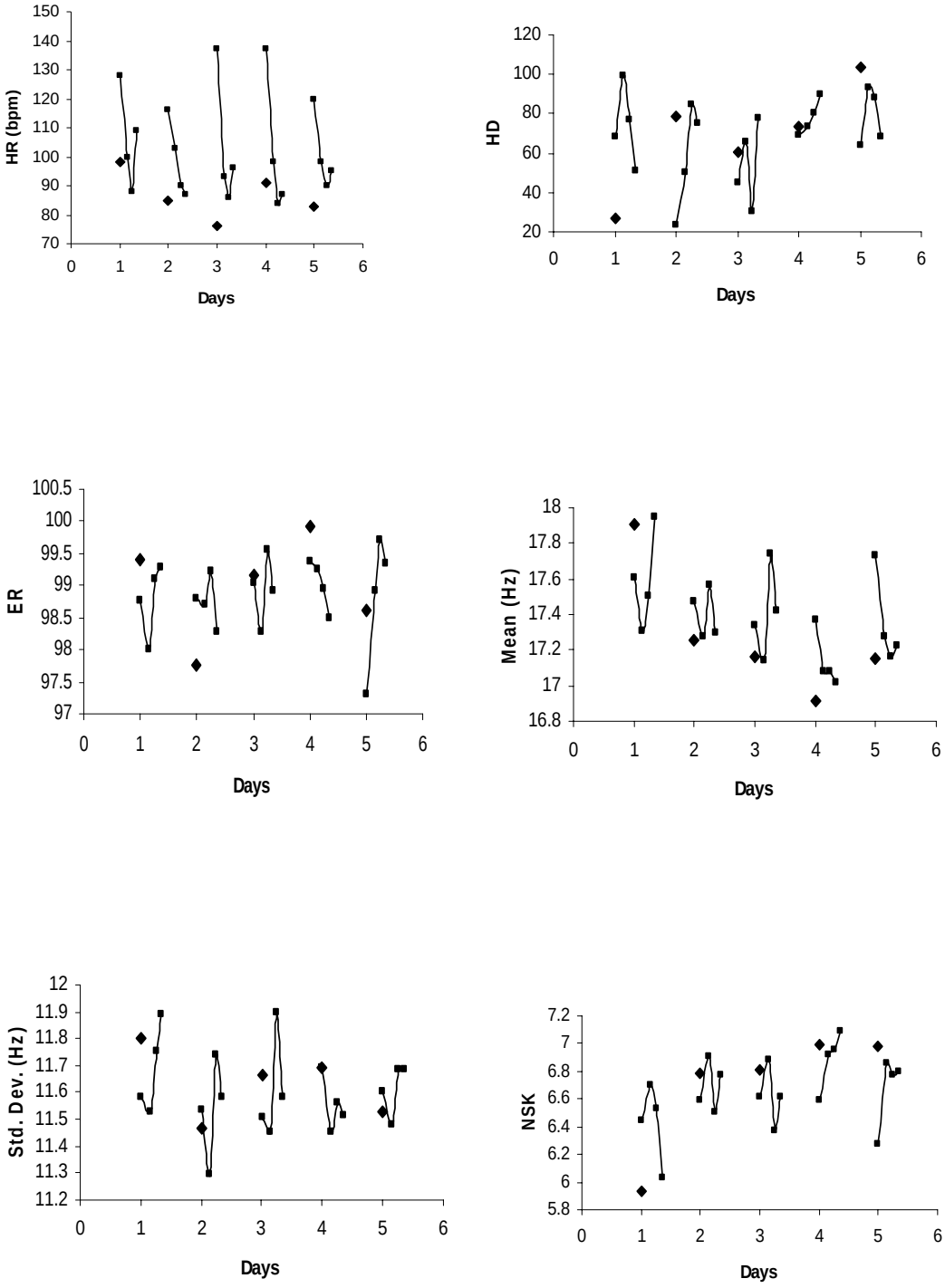

Fig. 4.1 (b) Plot of HR and RAP spectral parameters with exercise. Subject: S2_Nar

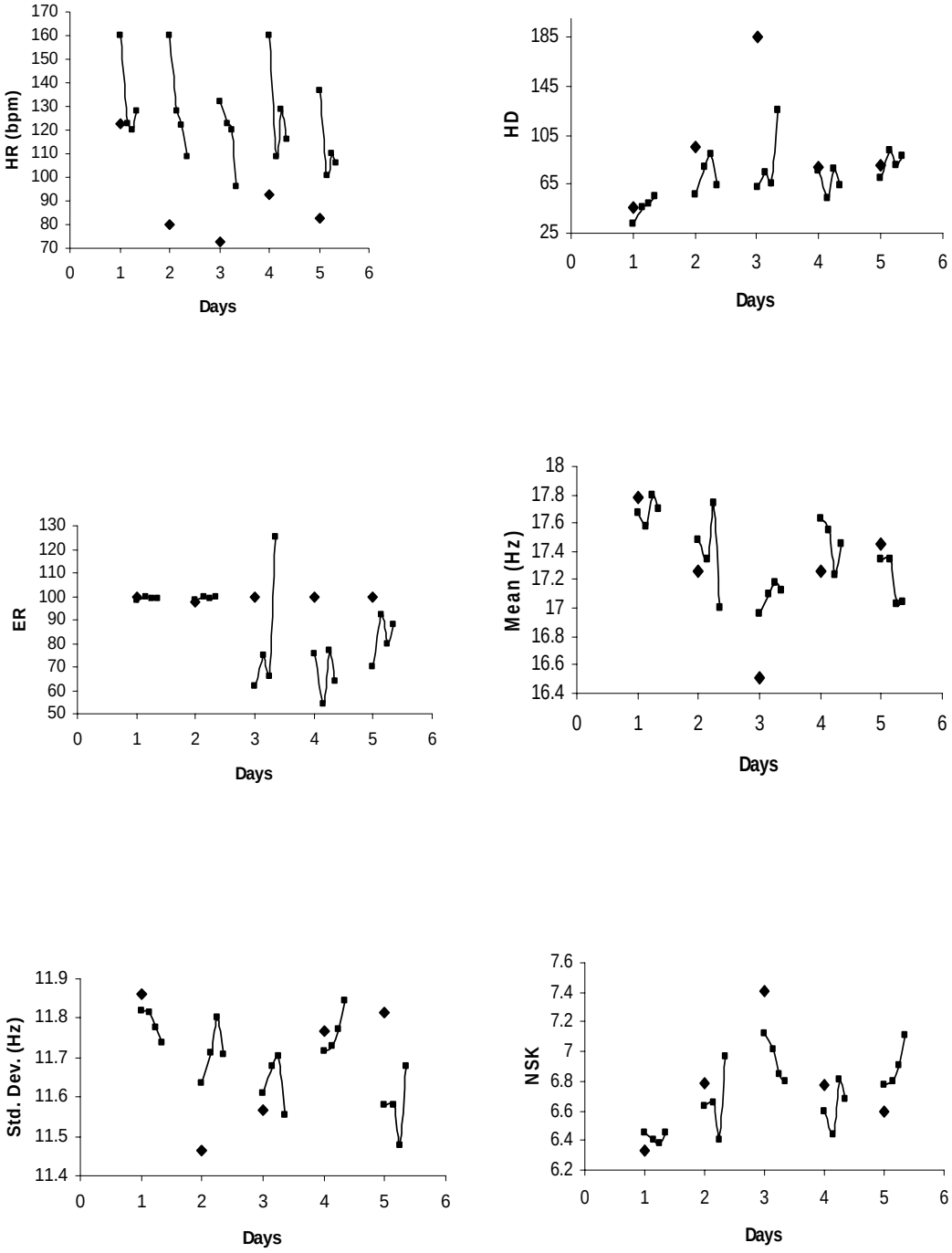

Fig. 4.1 (c) Plot of HR and RAP spectral parameters with exercise. Subject: S3_Nav

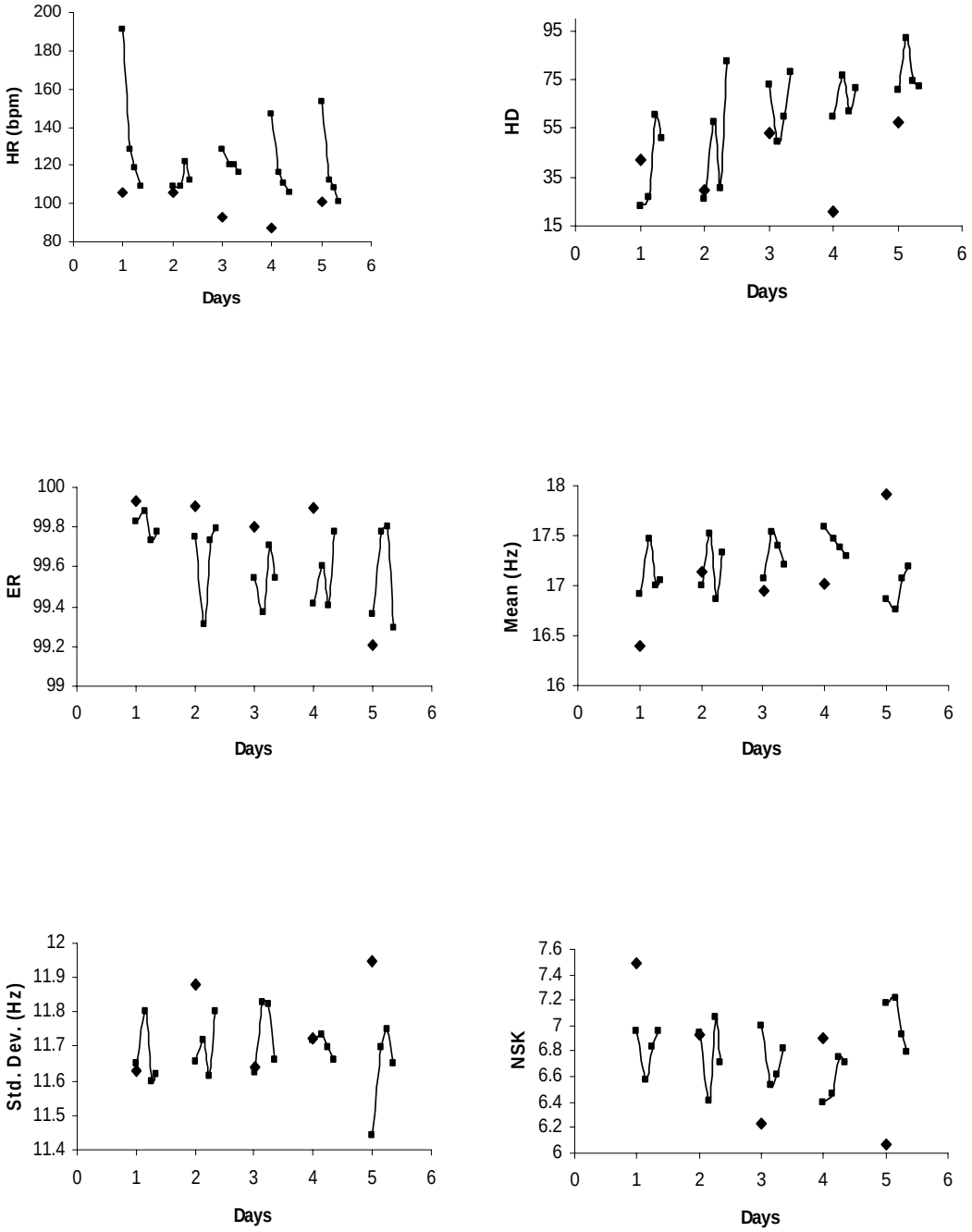

Fig. 4.1 (d) Plot of HR and RAP spectral parameters with exercise. Subject: S4_Sach

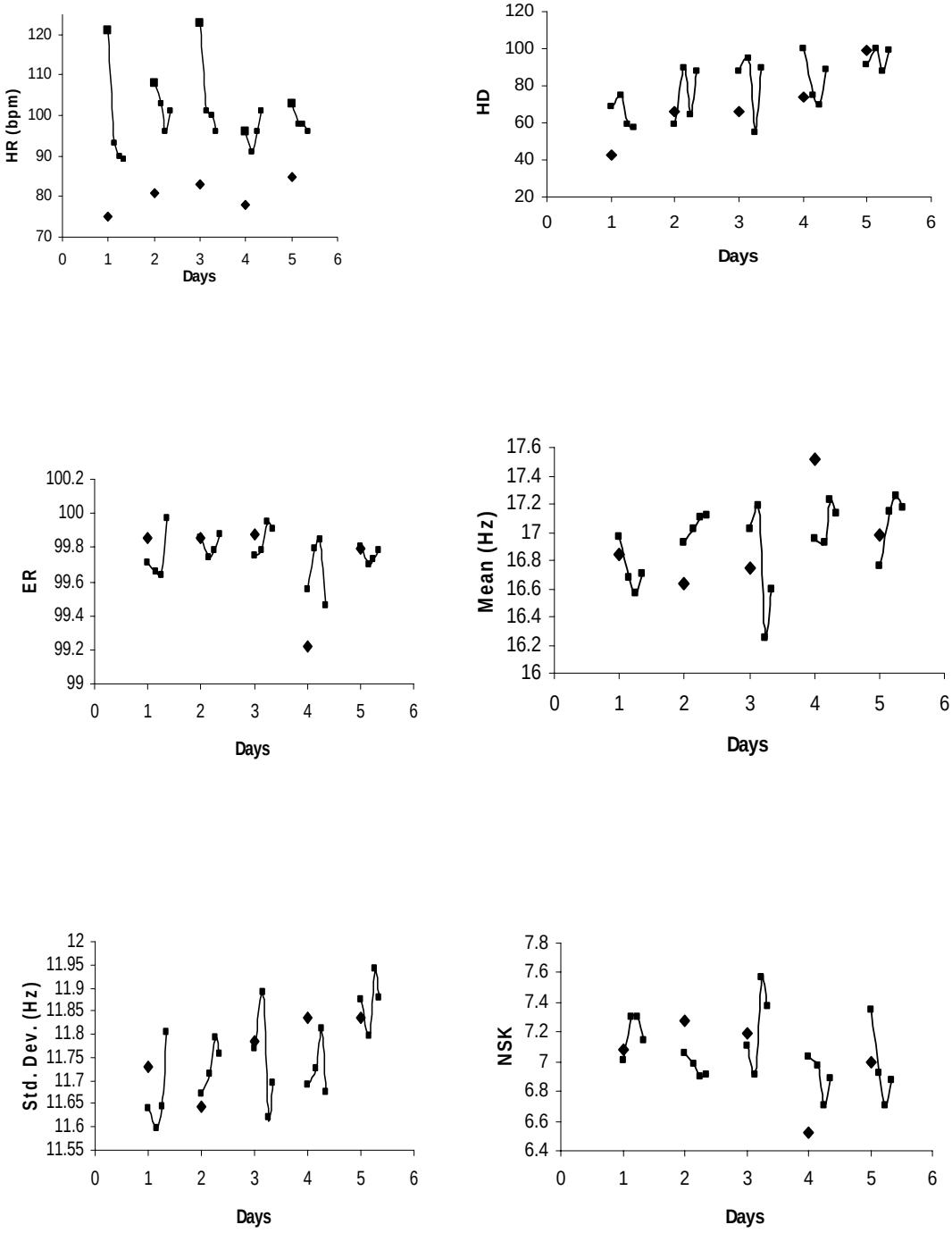

Fig. 4.1 (e) Plot of HR and RAP spectral parameters with exercise. Subject: S5_Mer

Table 4.8 Pre-Exercise HR and delays (obtained from cross-correlation peaks) between waveform pairs of all the subjects

Sub	Day	BP		HR	Delay (ms)					
		(mmHg)		(bpm)	ECG-RAP	PCG-RAP	RAP-PPG	ECG-PPG	ECG-PCG	PCG-PPG
S1	1	107	67	80	49.0	46.4	4.5	25.9	16.4	55.4
	2	94	64	83	44.0	2.4	2.0	9.3	10.8	7.4
	3	100	78	78	46.0	45	2.9	11.2	12.6	51.4
	4	111	76	96	36.0	45.2	10.0	16.2	12.5	52.5
	5	107	79	65	49.0	44.8	4.0	22.6	16.2	50.2
	Mean	104	73	80	44.8	45.7	4.7	17.0	13.7	51.2
	Std. Dev.	7	7	11	5.36	18.7	3.1	7.2	2.48	19.2
S2	1	120	67	98	50.0	52.5	3.0	13.6	2.5	54.9
	2	112	67	85	53.0	19.9	6.0	11.8	3.3	24.1
	3	94	63	76	58.0	24.9	6.0	15.3	3.7	35.2
	4	118	81	91	53.0	44.2	6.0	13	2.5	48.4
	5	105	70	83	45.5	49.9	11.5	14.7	2.9	58.5
	Mean	110	70	87	51.9	36.9	6.5	13.7	3.0	41.4
	Std. Dev.	11	7	8	4.6	12.8	3.1	1.4	0.5	9.1
S3	1	133	82	123	58	34.6	4	10.5	9.8	38.7
	2	113	73	80	49	23.6	4	9.9	13.2	28.1
	3	96	68	73	50	27.9	3	10.7	6.6	34.2
	4	109	74	93	49	15	6	9.9	16.2	20.1
	5	117	93	83	51	21.1	2	11.4	12.9	25.8
	Mean	114	78	90	51.4	27.7	3.8	10.5	11.7	31.7
	Std. Dev.	13	10	20	3.8	12.7	1.5	0.6	3.7	14.1
S4	1	156	120	106	13.7	26.1	3.1	6.9	4.9	29.3
	2	151	106	106	13.2	19.1	2.9	13.6	4.3	8.9
	3	171	109	93	14.0	7.8	2.6	14.5	4.1	27.8
	4	161	117	87	16.9	4.8	2.5	14.6	3.8	29.2
	5	152	106	101	4.9	8.4	2.6	15.4	3.4	28.9
	Mean	158	112	99	12.5	13.2	2.7	13	4.1	16.3
	Std. Dev.	8	7	8	4.5	9.0	0.3	3.5	0.6	9.2
S5	1	118	78	75	71.0	20.2	2.4	19.6	9.7	22.7
	2	118	79	81	66.3	22.6	2.1	33.8	6.2	23.6
	3	125	83	83	66.0	25.4	3.4	38.3	9.1	26.6
	4	140	87	78	13.8	20.3	4.5	40.1	6.1	21.4
	5	113	83	85	14.0	25.2	2.2	43.4	6.9	26.1
	Mean	123	82	80	46.2	25.0	2.9	35.04	7.6	27.9
	Std. Dev.	11	4	4	29.6	12.3	1.0	9.3	1.7	13.3
Total	**Mean**	122	83	87	41.4	27.1	4.1	16.9	7.9	33.2
	Std. Dev.	22	17	13	19.6	14.6	2.4	4.0	2.9	14.4

Table 4.9 HR and delays (obtained from cross-correlation peaks) between waveform pairs of subject S1_Bha

Day	Condition	BP	HR	Delay (ms)					
		(mmHg)	(bpm)	ECG-RAP	PCG-RAP	RAP-PPG	ECG-PPG	ECG-PCG	PCG-PPG
1	Pre-Ex	107/67	80	49	46.4	4.5	25.9	16.4	55.4
	Str-1	126/72	100	5.3	2.4	3.9	9.3	10.8	7.4
	Str-2		95	4.7	45	5.6	11.2	12.6	51.4
	Str-3		84	8.3	45.2	3.8	16.2	12.5	52.5
	Str-4	101/75	84	14.4	44.8	6	22.6	16.2	50.2
	Mean		89	16.3	36.8	4.8	17.0	13.7	43.4
	Std. Dev.		9	18.7	17.2	1.0	7.1	2.5	18.1
2	Pre-Ex	94/64	83	44	70	2	19.2	5.9	72
	Str-1	121/72	103	37	46.5	2.5	13.4	13.2	48.9
	Str-2		99	40	49.8	5	19.7	9.9	55.1
	Str-3		84	6	46.1	16.9	18.9	11.6	62.6
	Str-4	99/67	85	5	30.4	13.5	21.3	10.8	44.1
	Mean		91	26.4	48.6	8.0	18.5	10.3	56.5
	Std. Dev.		9	19.2	14.2	6.8	2.8	2.8	11.1
3	Pre-Ex	100/78	78	46	17.5	2.9	19.2	7.1	20.1
	Str-1	119/76	142	33	42.1	5.1	12	14.2	44.8
	Str-2		101	40	48	4	18.6	14.8	52.5
	Str-3		96	30	52.2	4.5	23.6	17.1	56.4
	Str-4	104/70	96	40	54.9	5	20.7	17.4	60.1
	Mean		103	37.8	42.9	4.3	18.8	14.1	46.8
	Std. Dev.		24	6.3	15	0.9	4.3	4.2	16
4	Pre-Ex	111/76	96	36	47.9	10	19.9	7.8	58.2
	Str-1	112/70	103	40	48.8	4.7	15.4	16	53.8
	Str-2		98	41	44.5	5	19	14.2	50.1
	Str-3		89	36	40.1	9	19.6	18.8	50.1
	Str-4	108/67	87	37	39.2	12.5	20	13.5	52.2
	Mean		95	38	44.1	8.2	18.8	14.1	52.9
	Std. Dev.		7	2.4	4.4	3.4	1.9	4.1	3.4
5	Pre-Ex	107/79	65	49	46.8	4	18.7	6.8	50.3
	Str-1	102/65	91	14	35.1	8	15.4	8.9	43.5
	Str-2		89	42	45.1	4	18.8	14.2	49.1
	Str-3		82	17	45.9	3.2	19.3	18.5	48.9
	Str-4	118/59	75	16	14.9	5.6	19.6	14.8	20.8
	Mean		80	27.6	37.6	5.0	18.4	12.6	42.5
	Std. Dev.		11	16.6	13.5	1.9	1.7	4.7	12.4
Total	**Mean**		91	29.2	42	6.1	18.3	12.9	48.4
	Std. Dev.		14	15.5	13.6	3.7	3.8	3.7	13.8

Table 4.10 HR and delays (obtained from cross-correlation peaks) between waveform pairs of subject S2_Nar

Day	Condition	BP	HR	Delay (ms)					
		(mmHg)	(bpm)	ECG-RAP	PCG-RAP	RAP - PPG	ECG-PPG	ECG-PCG	PCG-PPG
1	Pre-Ex	120/67	98	50	52.5	3	13.6	2.5	54.9
	Str-1	160/83	128	109	19.9	4.3	11.8	3.3	24.1
	Str-2		100	50	24.9	10	15.3	3.7	35.2
	Str-3		88	49	44.2	4	13	2.5	48.4
	Str-4	120/76	109	48	49.9	8.9	14.7	2.9	58.5
	Mean		105	61.2	38.3	6.0	13.7	3.0	44.2
	Std. Dev.		15	26.7	14.9	3.2	1.4	0.5	14.3
2	Pre-Ex	112/67	85	53	48.6	6	20.4	11.7	45.1
	Str-1	170/83	116	87	15	5	12.5	9.2	19.5
	Str-2		103	49	11.9	3.3	13.5	10.1	15
	Str-3		90	53	31.9	3.3	19.1	12.1	35.5
	Str-4	113/73	87	53.2	16.5	3.4	13.9	14.7	19.9
	Mean		96	59.0	24.8	4.2	15.9	11.6	27
	Std. Dev.		13	15.7	15.4	1.2	3.6	2.1	12.8
3	Pre-Ex	94/63	76	58	32.5	6	22.2	11.2	38.2
	Str-1	186/169	137	96	10.5	7.5	15.7	5.7	18
	Str-2		93	42	22.5	22	27	5.2	45
	Str-3		86	60	24.8	6.5	22.9	8.9	31.1
	Str-4	127/74	96	46	17.2	19	24.2	12.4	37.1
	Mean		97	60.4	21.5	12.2	22.4	8.7	33.9
	Std. Dev.		23	21.3	8.3	7.7	4.2	3.2	10.2
4	Pre-Ex	118/81	91	53	25	6	15.2	8.6	30.8
	Str-1	164/74	137	87	42.8	6.8	15.5	10.2	49.1
	Str-2		98	38	43.5	16	21.1	11.1	60.1
	Str-3		84	42	11.2	2.9	26.5	10.8	14
	Str-4	112/94	87	48.5	10.4	4.6	20.5	15	13.4
	Mean		99	53.7	26.6	7.3	19.8	11.1	33.5
	Std. Dev.		22	19.5	16.2	5.1	4.7	2.4	20.9
5	Pre-Ex	105/70	83	45.5	26	11.5	22	9.4	38.1
	Str-1	130/72	120	95	18.2	4.2	15.3	9.8	22.5
	Str-2		98	39.9	7.7	12.5	23.7	13.1	20
	Str-3		90	57	7.2	4	13.7	13.6	11.1
	Str-4	112/75	95	42.5	20.8	10.5	18.4	13.2	31.5
	Mean		97	56.0	16	8.5	18.6	11.8	24.6
	Std. Dev.		14	22.8	8.3	4.1	4.3	2.0	10.5
Total	**Mean**		99	58.1	25.4	7.6	18.0	9.2	32.6
	Std. Dev.		17	19.9	14.1	5.1	4.6	4.0	14.8

Table 4.11 HR and delays (obtained from cross-correlation peaks) between waveform pairs of subject S3_Nav

Day	Condition	BP	HR	Delay (ms)					
		(mmHg)	(bpm)	ECG-RAP	PCG-RAP	RAP - PPG	ECG-PPG	ECG-PCG	PCG-PPG
1	Pre-Ex	133/82	123	58	34.6	4	10.5	9.8	38.7
	Str-1	139/89	160	33.6	23.6	4.8	9.9	13.2	28.1
	Str-2		123	34.4	27.9	5.7	10.7	6.6	34.2
	Str-3		120	40.8	15	5	9.9	16.2	20.1
	Str-4	116/82	128	44.8	21.1	4.6	11.4	12.9	25.8
	Mean		131	42.3	24.4	4.8	10.5	11.7	29.4
	Std. Dev.		17	9.9	7.4	0.6	0.6	3.7	7.3
2	Pre-Ex	113/73	80	49	19.7	4	14.1	2.8	23.8
	Str-1	135/80	160	36.9	28.5	5.9	9.6	5.8	34.8
	Str-2		128	51	17.5	5.5	11.1	9.1	22.2
	Str-3		122	63	19.5	4.3	13.2	8.2	23.6
	Str-4	115/76	109	58.1	24.7	3.2	9.9	10.1	28.4
	Mean		120	51.6	22	4.6	11.6	7.2	26.6
	Std. Dev.		29	9.9	4.5	1.1	2.0	2.9	5.2
3	Pre-Ex	96/68	73	50	24.1	3	13.5	7.5	27.2
	Str-1	186/169	132	39.7	33.8	5.9	11.5	6.2	39.4
	Str-2		123	57.4	23.5	2.6	10.5	8.6	25.9
	Str-3		120	52.1	28.2	3.3	10.9	9.3	31.4
	Str-4	127/74	96	47.5	16.3	2	13.2	9.9	18.5
	Mean		109	49.3	25.2	3.4	11.9	8.3	28.5
	Std. Dev.		24	6.5	6.4	1.5	1.4	1.5	7.7
4	Pre-Ex	109/74	93	49	46.1	6	17.8	11.2	52.2
	Str-1	134/79	160	40.2	17.2	5.7	9.6	5.4	22.8
	Str-2		109	53.5	15.4	4.7	10.6	3.6	20.2
	Str-3		129	48.8	15.2	3.2	11.1	8.9	18
	Str-4	104/74	116	49.1	12.7	4.7	12.8	7.9	17.5
	Mean		121	48.1	21.3	4.9	12.4	7.4	26.1
	Std. Dev.		25	4.8	13.9	1.1	3.2	3.0	14.7
5	Pre-Ex	117/93	83	51	14.2	2	12.9	7.3	16.2
	Str-1	127/72	137	38.8	14.7	13.7	15.7	6	28.5
	Str-2		101	58.5	16.8	15.8	16.4	4.9	32.8
	Str-3		110	59.2	19.4	12.1	16.8	4.2	31.4
	Str-4	113/81	106	44.5	16.8	17.5	19.8	7.9	33.4
	Mean		107	50.4	16.4	12.2	16.3	6.1	28.5
	Std. Dev.		20	8.8	2.1	6.1	2.5	1.6	7.1
Total	**Mean**		118	48.4	21.9	6.0	12.6	8.1	27.8
	Std. Dev.		23	8.2	7.9	4.2	2.8	3.1	8.3

Table 4.12 HR and delays (obtained from cross-correlation peaks) between waveform pairs of subject S4_Sach

Day	Condition	BP	HR	Delays (ms)					
		(mmHg)	(bpm)	ECG-RAP	PCG-RAP	RAP-PPG	ECG-PPG	ECG-PCG	PCG-PPG
1	Pre-Ex	156/120	106	13.7	26.1	3.1	6.9	4.9	29.3
	Str-1	177/134	191	13.1	7.3	1.7	13.6	4.3	8.9
	Str-2		128	13.3	26.5	1.2	14.5	4.1	27.8
	Str-3		119	13	27.5	1.7	14.6	3.8	29.2
	Str-4	164/119	109	13.6	26.9	1.9	15.4	3.4	28.9
	Mean		131	13.3	22.9	1.9	13.0	4.1	24.8
	Std. Dev.		35	0.3	8.7	0.7	3.5	0.6	8.9
2	Pre-Ex	151/106	106	13.2	19.1	2.9	17.2	7	22.1
	Str-1	159/145	109	10.7	14.1	5.1	14.8	4.5	18.9
	Str-2		109	15.3	11.8	2.7	17.9	6.9	14.6
	Str-3		122	15.1	23.2	2.8	18.2	5.5	25
	Str-4	151/120	112	11.5	26.5	2.7	15.2	5.2	29.2
	Mean		112	13.2	18.9	3.2	16.7	5.8	22
	Std. Dev.		6	2.1	6.1	1.0	1.6	1.1	5.6
3	Pre-Ex	171/109	93	14	7.8	2.6	15.4	6.2	10.5
	Str-1	177/111	128	14.1	29.1	4.1	17.6	5.8	33.2
	Str-2		120	14.5	29.1	3.6	16.3	5.4	32.1
	Str-3		120	14.3	30.5	2.7	16.5	4.8	32.1
	Str-4	152/113	116	6.6	28.5	4.2	16.2	4.8	32.6
	Mean		115	12.7	25	3.4	16.4	5.4	28.1
	Std. Dev.		13	3.4	9.6	0.8	0.8	0.6	9.8
4	Pre-Ex	161/117	87	16.9	4.8	2.5	16.6	7.2	7.3
	Str-1	187/169	147	5	16.5	3.5	14.4	7	20.1
	Str-2		116	13.4	17.1	2.4	16.8	6.5	20.5
	Str-3		111	10.1	20.1	3.3	16.8	6.8	23.2
	Str-4	159/119	106	13.3	27	3.1	17.5	6.5	30.1
	Mean		113	11.7	17.1	3.0	16.4	6.8	20.2
	Std. Dev.		22	4.5	8	0.5	1.2	0.3	8.3
5	Pre-Ex	152/106	101	4.9	8.4	2.6	15.3	4.5	12.1
	Str-1	224/206	153	5.5	17.3	5.9	11.3	2.7	23.3
	Str-2		112	5.4	21.2	4.7	9.9	7.2	26.9
	Str-3		108	6.1	26.1	3.5	10.8	4.5	29.2
	Str-4	158/106	101	14.7	28.4	3.1	17.2	5.2	31.6
	Mean		115	7.3	20.3	4.0	12.9	4.8	24.6
	Std. Dev.		22	4.1	7.9	1.3	3.2	1.6	7.6
Total	**Mean**		117	11.7	20.8	3.1	15.1	5.4	23.9
	Std. Dev.		21	3.8	8	1.1	2.8	1.3	8

Table 4.13 HR and delays (obtained from cross-correlation peaks) between waveform pairs of subject S5_Mer

Day	Condition	BP	HR	Cross-correlation peaks (ms)					
		(mmHg)	(bpm)	ECG-RAP	PCG-RAP	RAP-PPG	ECG-PPG	ECG-PCG	PCG-PPG
1	Pre-Ex	118/78	75	71	20.2	2.4	19.6	9.7	22.7
	Str-1	151/136	121	14	22.6	0.9	33.8	6.2	23.6
	Str-2		93	10.4	25.4	1.15	38.3	9.1	26.6
	Str-3		90	7	20.3	1.1	40.1	6.1	21.4
	Str-4	120/79	89	12.2	25.2	0.9	43.4	6.9	26.1
	Mean		94	22.9	22.7	1.3	35.0	7.6	24.1
	Std. Dev.		17	27.0	2.5	0.6	9.3	1.7	2.2
2	Pre-Ex	118/79	81	66.3	13.7	2.1	15.2	7.2	15.8
	Str-1	145/86	108	60.3	10.7	2	13.1	8	12.7
	Str-2		103	49.8	10.4	2.5	13.8	12.9	12.9
	Str-3		96	57.4	11.8	2.3	17.8	13.3	14.1
	Str-4	113/81	101	60.5	14.6	1.5	16.4	7	16.1
	Mean		98	58.9	12.2	2.1	15.3	9.7	14.3
	Std. Dev.		10	6.0	1.8	0.4	1.9	3.1	1.6
3	Pre-Ex	125/83	83	66	34	3.4	18.7	8.6	37.4
	Str-1	173/156	123	6.9	30.2	3.3	10.7	4.6	33.5
	Str-2		101	13.8	28.2	2.9	16.4	9.6	30.7
	Str-3		100	15.6	21.1	1.1	18.3	8.9	22.2
	Str-4	126/86	96	16	19.2	2.2	19.6	8.8	21.1
	Mean		101	23.7	26.5	2.6	16.7	8.1	29
	Std. Dev.		14	24.0	6.2	1.0	3.6	2.0	7.1
4	Pre-Ex	140/87	78	13.8	41.7	4.5	16.7	7.8	46.2
	Str-1	133/79	96	10.4	34.3	2.3	10.8	4.8	36.6
	Str-2		91	13.4	33.9	2.8	16.5	5.5	36.9
	Str-3		96	14.4	41.2	3.8	18	5.7	45.1
	Str-4	123/90	101	14.4	43.1	3.7	19.1	5.5	46.7
	Mean		92	13.3	38.8	3.4	16.2	5.9	42.3
	Std. Dev.		9	1.7	4.4	0.9	3.2	1.1	5.1
5	Pre-Ex	113/83	85	14	15.2	2.2	15.4	7.9	17.4
	Str-1	125/77	103	8.5	10.1	3.3	14.5	6	13.4
	Str-2		98	13.3	11.3	2.9	14.3	6.2	14.2
	Str-3		98	16	20.5	2.8	19.8	7.3	23.2
	Str-4	122/81	96	14.5	21.1	4.6	18.9	7.8	25.3
	Mean		96	13.3	15.6	3.2	16.6	7.0	18.7
	Std. Dev.		7	2.8	5.1	0.9	2.6	0.9	5.3
Total	**Mean**		96	26.4	23.2	2.5	20.0	7.7	25.7
	Std. Dev.		11	22.8	10.3	1.1	8.9	2.2	10.8

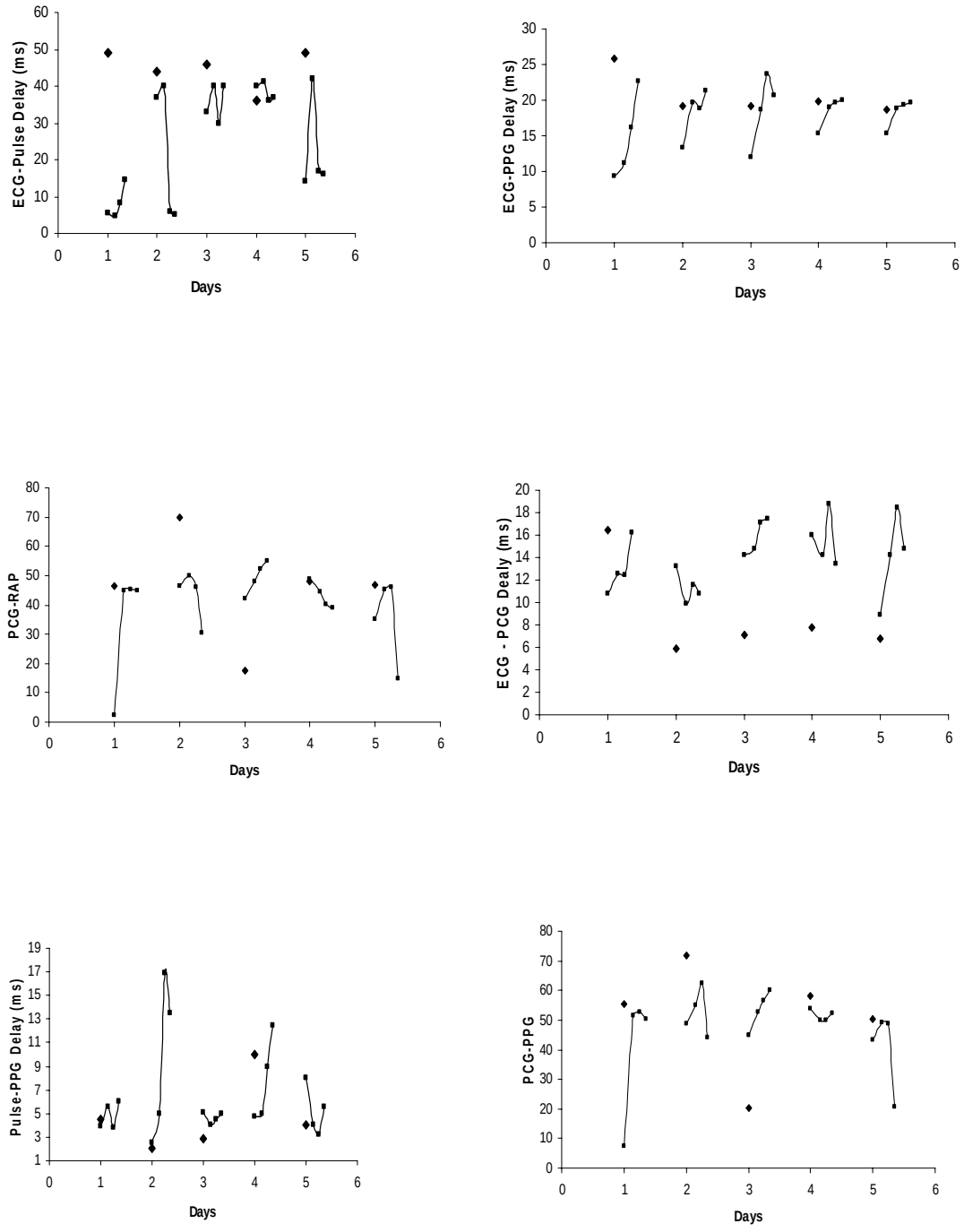

Fig. 4.2 (a): Plots of Delays with exercise. Subject: S1_Bha

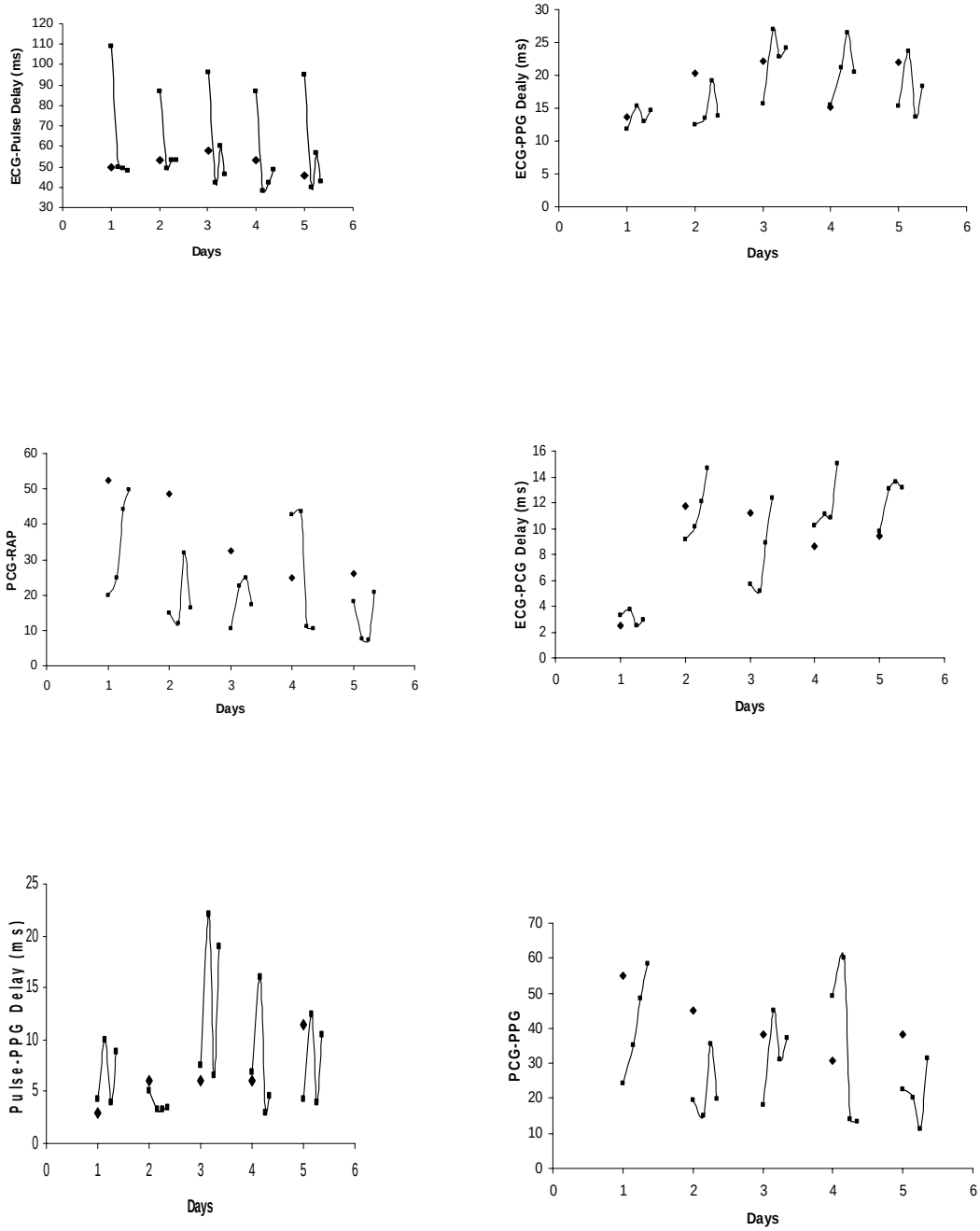

Fig. 4.2 (b): Plots of Delays with exercise. Subject: S2_Nar

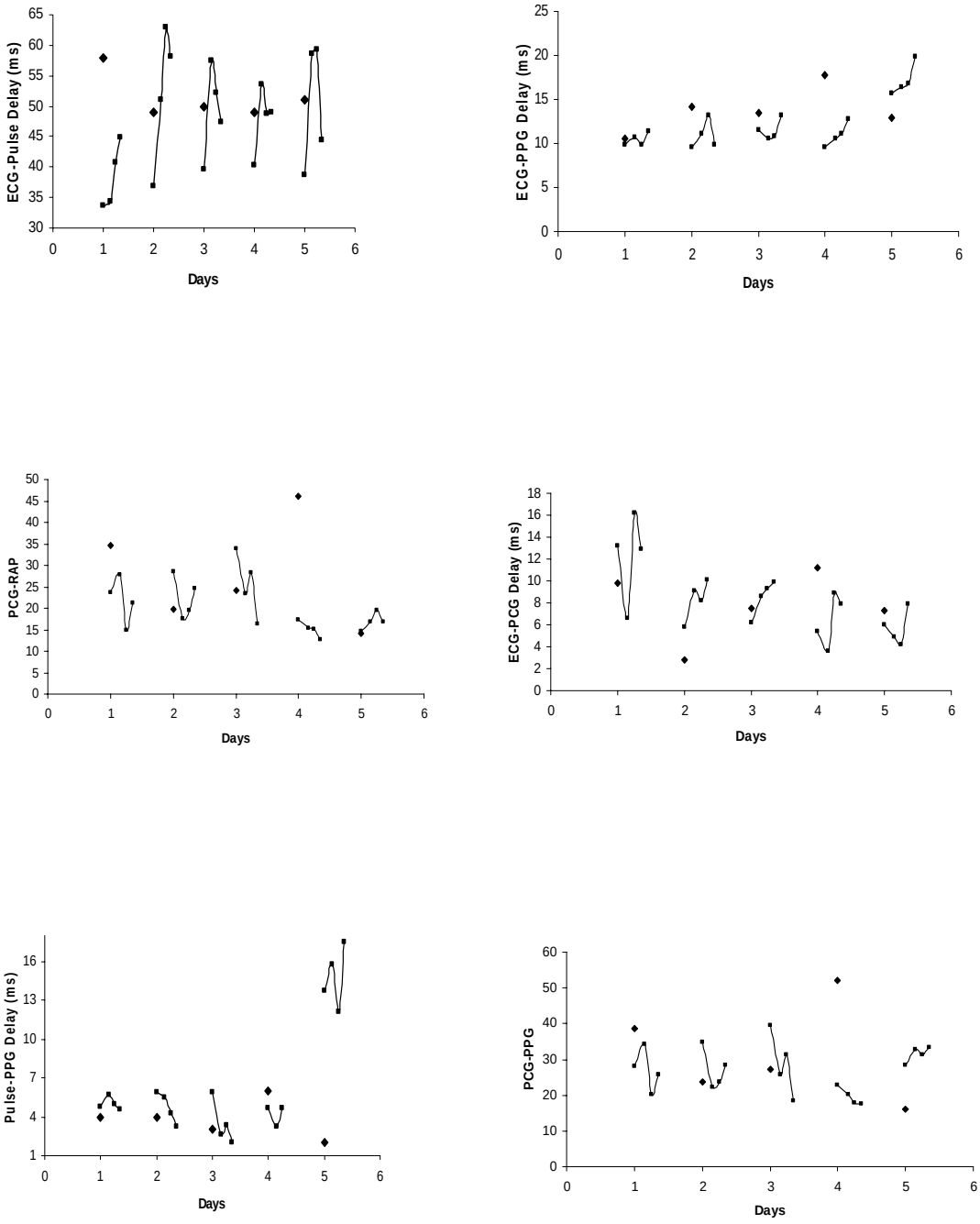

Fig. 4.2 (c): Plots of Delays with exercise. Subject: S3_Nav

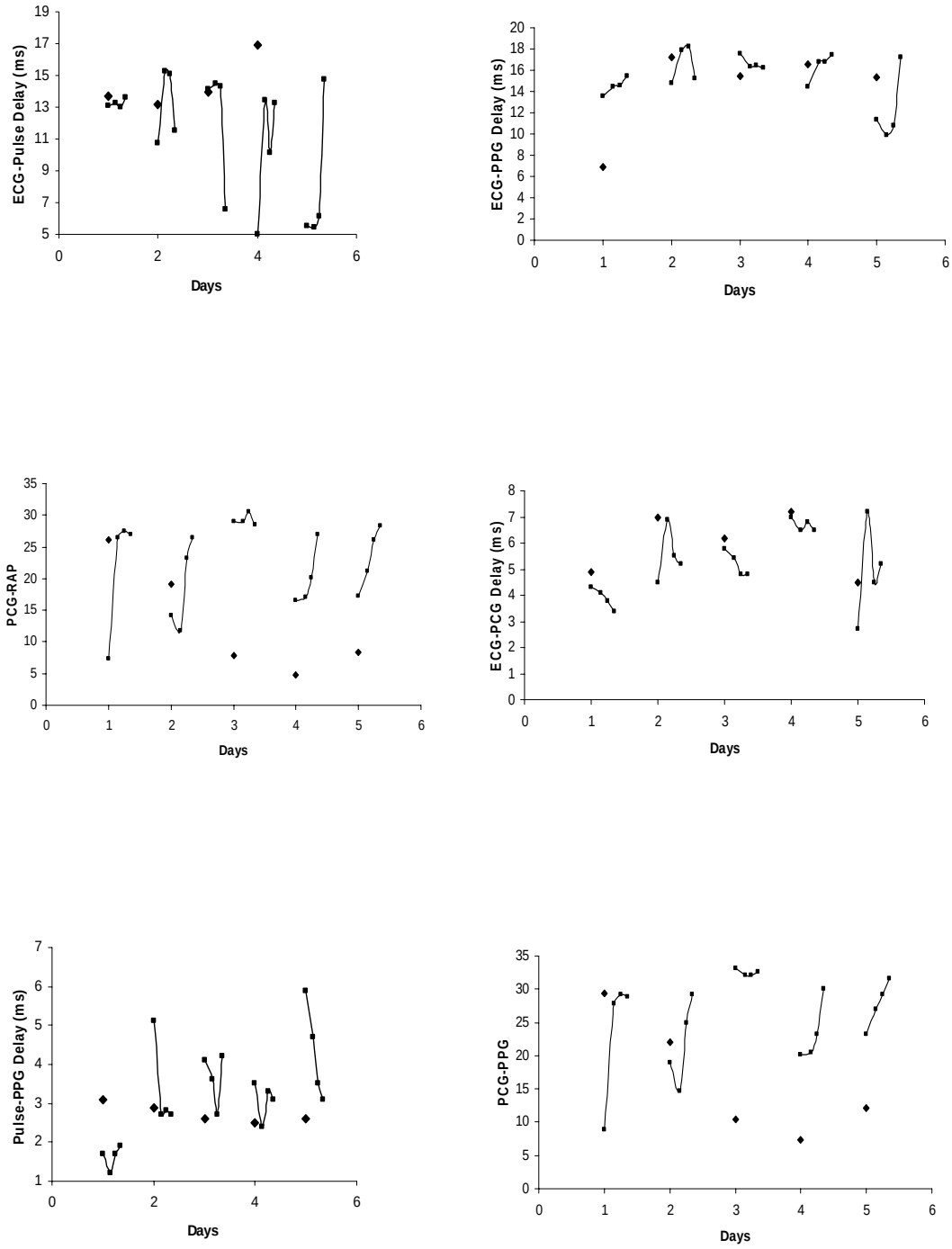

Fig. 4.2 (d) Plots of Delays with exercise. Subject: S4_Sach

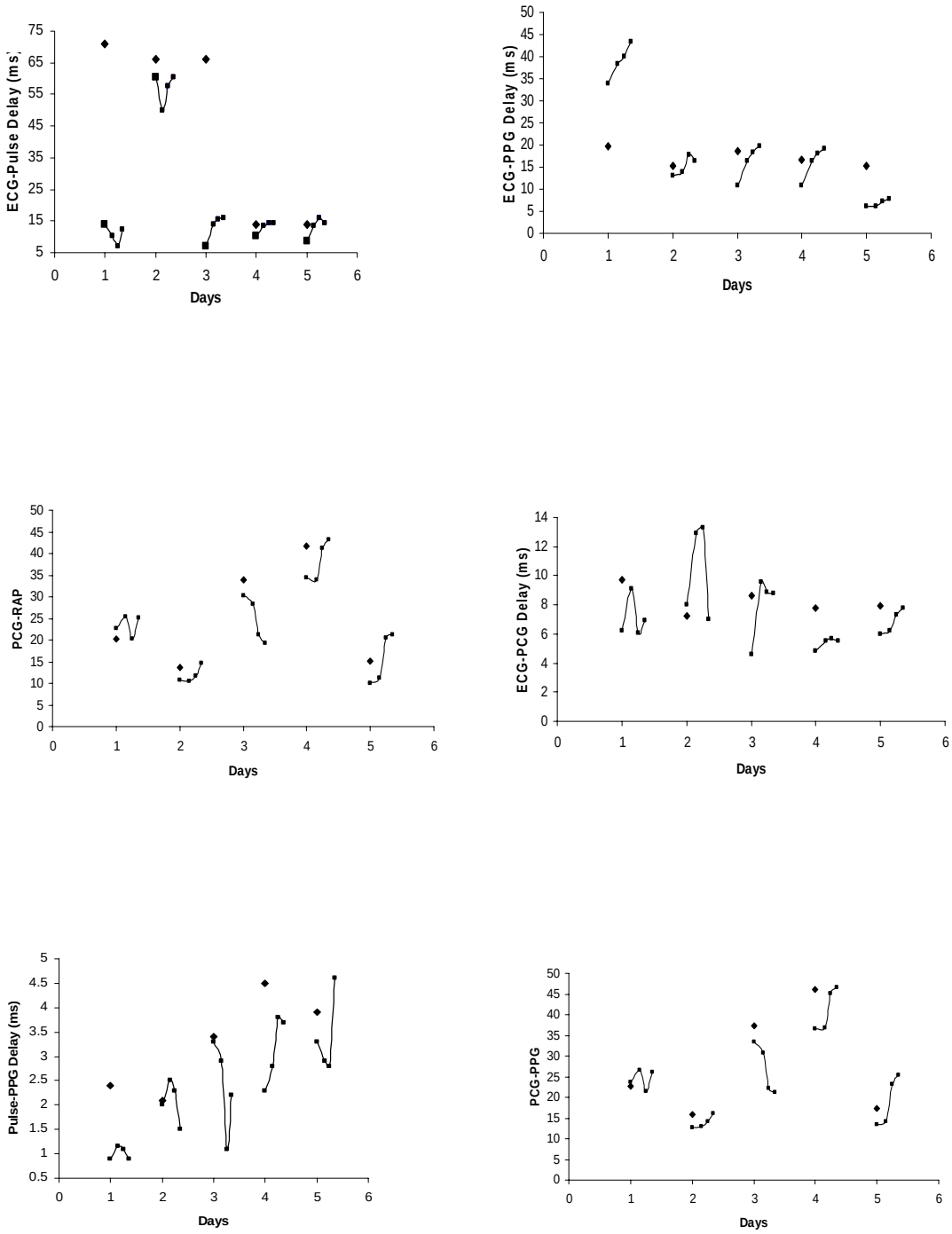

Fig. 4.2 (e) Plots of Delays with exercise. Subject: S5_Mer

Table 4.14: Pre-exercise correlation across the subjects

Parameters		HR	Spectral					Delay					
			ER	HD	Mean	Std. Dev.	NSK	ECG - RAP	PCG - RAP	RAP-PPG	ECG - PPG	ECG - PCG	PCG - PPG
HR		1	0	-0.44	0.28	0.21	-0.3	-0.34	-0.15	0.01	-0.51	-0.17	0.15
Spectral	**ER**	0.03	1	-0.21	-0.4	0.52	0.29	-0.1	-0.04	-0.54	-0.17	0	-0.2
	HD	-0.44	-0.2	1	-0.26	-0.39	0.34	0.18	0.32	0.21	0	0.1	0.37
	Mean	0.28	-0.4	-0.26	1	0.46	-0.89	-0.1	-0.38	0.18	0.11	-0.01	0.07
	Std. Dev.	0.21	0.5	-0.39	0.46	1	-0.38	-0.24	-0.3	-0.41	-0.02	0.07	-0.02
	NSK	-0.3	0.3	0.34	-0.89	-0.38	1	0.21	0.44	-0.1	-0.08	0.12	0.08
Delay	**ECG-RAP**	-0.34	-0.1	0.18	-0.1	-0.24	0.21	1	0.39	0.14	0.27	0.35	0
	PCG-RAP	-0.15	-0	0.32	-0.38	-0.3	0.44	0.39	1	0.41	0.04	0.06	-0.01
	RAP-PPG	0.01	-0.5	0.21	0.18	-0.41	-0.1	0.14	0.41	1	0.43	0.35	0.19
	ECG-PPG	-0.51	-0.2	0	0.11	-0.02	-0.08	0.27	0.04	0.43	1	0.63	0.03
	PCG-PPG	-0.17	0	0.1	-0.01	0.07	0.12	0.35	0.06	0.35	0.63	1	0.19
	ECG-PPG	0.15	-0.2	0.37	0.07	-0.02	0.08	0	-0.01	0.19	0.03	0.19	1

Table 4.15: Correlation results of S1_Bha

Parameters		HR	Spectral					Delay					
			ER	HD	Mean	Std. Dev.	NSK	ECG - RAP	PCG - RAP	RAP - PPG	ECG- PPG	ECG- PCG	PCG- PPG
HR		1	-0.16	-0.45	0.13	-0.02	-0.12	0.04	-0.34	-0.09	-0.49	0.21	-0.05
Spectral	**ER**	-0.16	1	-0.32	-0.03	0.58	-0.05	0.16	0.06	-0.66	-0.08	-0.19	0.31
	HD	-0.45	-0.32	1	-0.38	-0.48	0.40	0.06	0.19	0.22	0.41	0.14	-0.19
	Mean	0.13	-0.03	-0.38	1	0.63	-0.95	-0.64	-0.05	-0.01	-0.38	0.13	0.30
	Std. Dev.	-0.02	0.58	-0.48	0.63	1	-0.62	-0.32	0.01	-0.42	-0.37	-0.11	0.38
	NSK	-0.12	-0.05	0.40	-0.95	-0.62	1	0.55	-0.14	0.13	0.37	-0.03	-0.32
Delay	**ECG-RAP**	0.04	0.16	0.06	-0.64	-0.32	0.55	1	0.28	-0.38	0.34	-0.04	-0.3
	PCG-RAP	-0.34	0.06	0.19	-0.05	0.01	-0.14	0.28	1	-0.11	0.33	-0.45	-0.19
	RAP - PPG	-0.09	-0.66	0.22	-0.01	-0.42	0.13	-0.38	-0.11	1	0.18	-0.05	-0.38
	ECG-PPG	-0.49	-0.08	0.41	-0.38	-0.37	0.37	0.34	0.33	0.18	1	0.22	-0.41
	ECG-PCG	0.21	-0.19	0.14	0.13	-0.11	-0.03	-0.04	-0.45	-0.05	0.22	1	0.08
	PCG-PPG	-0.05	0.31	-0.19	0.30	0.38	-0.32	-0.3	-0.19	-0.38	-0.41	0.08	1

Table 4.16: Correlation results of S2_Nar

Parameters		HR	Spectral					Delay					
			ER	HD	Mean	Std. Dev.	NSK	ECG-RAP	PCG - RAP	RAP - PPG	ECG-PPG	ECG-PCG	PCG-PPG
HR		1	-0.07	-0.35	0.36	-0.07	-0.39	0.79	-0.47	-0.05	-0.49	-0.35	-0.26
Spectral	**ER**	-0.07	1	-0.23	-0.03	0.52	-0.07	-0.16	0.07	-0.07	-0.07	-0.03	-0.31
	HD	-0.35	-0.23	1	-0.54	-0.28	0.57	-0.36	0.13	0.2	0.29	0.35	0.28
	Mean	0.36	-0.03	-0.54	1	0.58	-0.97	0.34	-0.33	-0.23	-0.38	-0.51	-0.09
	Std. Dev.	-0.07	0.52	-0.28	0.58	1	-0.66	0.04	0.04	-0.27	-0.19	-0.27	-0.19
	NSK	-0.39	-0.07	0.57	-0.97	-0.66	1	-0.36	0.33	0.23	0.42	0.57	0.23
Delay	**ECG-RAP**	0.79	-0.16	-0.36	0.34	0.04	-0.36	1	-0.43	-0.36	-0.51	-0.24	0.1
	PCG-RAP	-0.47	0.07	0.13	-0.33	0.04	0.33	-0.43	1	0.56	0.57	0.04	-0.04
	RAP - PPG	-0.05	-0.07	0.2	-0.23	-0.27	0.23	-0.36	0.56	1	0.58	-0.02	-0.21
	ECG-PPG	-0.49	-0.07	0.29	-0.38	-0.19	0.42	-0.51	0.57	0.58	1	0.35	0.07
	ECG-PCG	-0.35	-0.03	0.35	-0.51	-0.27	0.57	-0.24	0.04	-0.02	0.35	1	0.4
	PCG-PPG	-0.26	-0.31	0.28	-0.09	-0.19	0.23	0.1	-0.04	-0.21	0.07	0.4	1

Table 4.17: Correlation results of S3_Nav

Parameters		HR	Spectral					Delay					
			ER	HD	Mean	Std. Dev.	NSK	ECG - RAP	PCG - RAP	RAP - PPG	ECG- PPG	ECG- PCG	PCG- PPG
HR		1	-0.13	-0.63	0.49	0.3	-0.39	-0.48	-0.11	0.05	-0.51	0.16	0.17
Spectral	**ER**	-0.14	1	0.22	-0.37	0.25	0.31	0.23	-0.33	-0.25	-0.01	0.15	0.18
	HD	-0.63	0.22	1	-0.69	-0.52	0.66	0.28	-0.08	-0.01	0.4	-0.23	0
	Mean	0.49	-0.37	-0.69	1	0.62	-0.96	-0.18	0.05	-0.1	-0.37	0.28	-0.16
	Std. Dev.	0.3	0.25	-0.52	0.62	1	-0.6	-0.07	-0.03	-0.34	-0.4	0.52	0.2
	NSK	-0.4	0.31	0.66	-0.96	-0.6	1	0.14	-0.1	0.2	0.41	-0.26	0.2
Delay	**ECG- RAP**	-0.49	0.23	0.28	-0.18	-0.07	0.14	1	-0.27	-0.05	0.21	-0.16	-0.09
	PCG- RAP	-0.12	-0.33	-0.08	0.05	-0.03	-0.1	-0.27	1	0.06	0.02	0	0.01
	RAP - PPG	0.05	-0.25	-0.01	-0.1	-0.34	0.2	-0.05	0.06	1	0.71	-0.3	-0.21
	ECG- PPG	-0.51	-0.01	0.4	-0.37	-0.4	0.41	0.21	0.02	0.71	1	-0.26	-0.16
	ECG- PCG	0.16	0.15	-0.23	0.28	0.52	-0.26	-0.16	0	-0.3	-0.26	1	0.37
	PCG- PPG	0.17	0.18	0	-0.16	0.2	0.2	-0.09	0.01	-0.21	-0.16	0.37	1

Table 4.18: Correlation results of S4_Sach

Parameters		HR	Spectral					Delay					
			ER	HD	Mean	Std. Dev.	NSK	ECG - RAP	PCG - RAP	RAP - PPG	ECG- PPG	ECG- PCG	PCG- PPG
HR		1	-0.08	-0.12	-0.06	-0.29	0.16	-0.2	0.08	0.04	-0.18	-0.34	0.08
Spectral	**ER**	-0.08	1	-0.38	-0.58	-0.04	0.44	0.32	0.14	-0.31	-0.28	0.01	-0.37
	HD	-0.12	-0.38	1	0.15	-0.1	-0.07	-0.46	0.18	0.37	-0.11	0.07	0.21
	Mean	-0.06	-0.58	0.15	1	0.66	-0.85	-0.14	-0.23	-0.23	0.55	0.17	0.51
	Std. Dev.	-0.29	-0.04	-0.1	0.66	1	-0.55	-0.02	-0.28	-0.35	0.23	0.3	0.36
	NSK	0.16	0.44	-0.07	-0.85	-0.55	1	0.03	0.26	0.35	-0.51	-0.21	-0.37
Delay	**ECG- RAP**	-0.2	0.32	-0.46	-0.14	-0.02	0.03	1	0.15	-0.53	0.46	0.16	-0.35
	PCG- RAP	0.08	0.14	0.18	-0.23	-0.28	0.26	0.15	1	-0.29	-0.2	-0.26	-0.28
	RAP - PPG	0.04	-0.31	0.37	-0.23	-0.35	0.35	-0.53	-0.29	1	-0.26	0	0.16
	ECG- PPG	-0.18	-0.28	-0.11	0.55	0.23	-0.51	0.46	-0.2	-0.26	1	0.32	0.23
	ECG- PCG	-0.34	0.01	0.07	0.17	0.3	-0.21	0.16	-0.26	0	0.32	1	0.33
	PCG- PPG	0.08	-0.37	0.21	0.51	0.36	-0.37	-0.35	-0.28	0.16	0.23	0.33	1

Table 4.19: Correlation results of S5_Meru

Parameters		HR	Spectral					Delay					
			ER	HD	Mean	Std. Dev.	NSK	ECG-RAP	PCG - RAP	RAP - PPG	ECG-PPG	ECG-PCG	PCG-PPG
HR		1	0.08	0.29	0.08	-0.09	0.05	-0.29	-0.22	-0.12	-0.1	-0.21	-0.28
Spectral	**ER**	0.08	1	-0.27	-0.53	0	0.5	0.34	0.28	-0.39	0.04	0.2	-0.25
	HD	0.29	-0.27	1	0.44	0.43	-0.28	-0.42	-0.35	0.41	-0.43	-0.2	-0.27
	Mean	0.08	-0.53	0.44	1	0.61	-0.96	-0.07	-0.4	0.64	-0.35	-0.05	-0.17
	Std. Dev.	-0.09	0	0.43	0.61	1	-0.56	-0.15	-0.06	0.59	-0.29	0.02	-0.35
	NSK	0.05	0.5	-0.28	-0.96	-0.56	1	0.03	0.37	-0.57	0.25	0.04	0.07
Delay	**ECG-RAP**	-0.29	0.34	-0.42	-0.07	-0.15	0.03	1	0.16	-0.09	-0.26	0.51	-0.24
	PCG-RAP	-0.22	0.28	-0.35	-0.4	-0.06	0.37	0.16	1	-0.33	0.59	0.16	0.3
	RAP - PPG	-0.12	-0.39	0.41	0.64	0.59	-0.57	-0.09	-0.33	1	-0.57	-0.12	-0.46
	ECG-PPG	-0.1	0.04	-0.43	-0.35	-0.29	0.25	-0.26	0.59	-0.57	1	-0.03	0.78
	ECG-PCG	-0.21	0.2	-0.2	-0.05	0.02	0.04	0.51	0.16	-0.12	-0.03	1	-0.14
	PCG-PPG	-0.28	-0.25	-0.27	-0.17	-0.35	0.07	-0.24	0.3	-0.46	0.78	-0.14	1

4.4 Discussion

First let us look at the results from recordings taken at rest on the five subjects in Table 4.1. We see that all the subjects had HR under resting condition much higher than the average rate of 72 bpm for persons with normal health. The rate was generally high in all the sessions. For four of the subjects the blood pressure readings can be considered normal. However, for subject S4, the blood pressure recorded (both systolic and diastolic) was much higher than the normal on all the days. SER values from the spectral analysis of RAP waveform are constantly about or above 99%, which indicates normal pulse according to an earlier report [11]. There is very small variability across the days and across the subjects. Harmonic distortion (HD) of RAP waveform varies over 41-97 across the subjects, with relatively large variation across the recording sessions for each subject. For subject S4, with unusually high BP, the HD values are in the low range, 21-58 with a mean of 41. The three statistical measures on the log power spectrum show a very narrow variation across days and across subjects. Averaged across subjects, the mean frequency (SMF) is 17.2 Hz, the standard deviation (SDF) is 11.7 Hz, and the normalized skewness (NSK) is 6.8.

Under pre-exercise condition, there was a variation across the days and across the subjects for all the six delay values. It was noted that for subject S4, with high BP, all the delays are relatively smaller. Average ECG-PCG delay is 7.9 ms. Average value of PCG-RAP delay, indicating the travel time of the pulse pressure wave from the heart valves to the radial artery is 27.1 ms. For five subjects the values vary over 21-45 ms, while for subject S4 it is unusually low, 13.2 ms. The delay between the RAP and PPG may be taken as indicative of delay between pressure pulse and volumetric flow. The average value is 4.1 ms, with a large variation across the sessions. However, this delay for subject S4 is relatively small, 2.7 ms. A small delay may be indicative of highly pulsatile flow, because of low compliance of arteries.

Under exercise condition, the ECG-PCG delay values do not show any constant pattern across the days and across the subjects. *PCG-RAP delay:* For subjects S1, there is a large fall in the value, followed by a recovery with different pattern on different days. For subject S2, S3, S5 the pattern is the same as for S1 on 3 days. For subject S4, the patterns very across days and show a very large variation. *RAP-PPG delay:* There are often large variations after the exercise and during the relaxation phase. But there are no clear patterns, probably indicative of different patterns in changes in blood supply during exercise and the relaxation phase.

It may be noted here that selection of subjects in this exploratory investigation was not controlled and the level of exercise and time of the recordings were also controlled. We may be able to see more consistent patterns with recordings under controlled conditions from a larger number of subjects, healthy as well as with different diagnosed disorders. It is observed that various propagation delays with respect to first heart sound matches by adding delays on the partial paths. i.e. delay between first heart sound and PPG is equal to the sum of the delays between first heart sound and RAP, and between RAP and PPG. But with respect to ECG the delays are not matching by adding delays on partial path. Pre-processing of ECG waveform for enhancing QRS complex and suppressing P and T segment, may improve consistency in measurement of delays by different methods.

The correlation coefficients between pairs of the 12 parameters were calculated, without any apriori hypotheses or their inter relationship. Under rest condition, the HR values have significant correlation with HD (-0.44), ECG-RAP delay (-0.34), and ECG-PPG delay (-0.51). The correlation across the subjects under various exercise condition do not indicate any clear pattern.

Chapter 5
SUMMARY AND CONCLUSIONS

In this project, a multi-channel recording set-up has been developed and used for an exploratory study of diagnostic information in the radial arterial pulse waveform and other physiologically related waveforms: ECG, PCG, and PPG. The RAP waveform has been analyzed for spectral parameters, and the timing relations between the four waveforms have been studied by cross-correlation peaks. The recordings were made under rest, and at regular interval during post-exercise relaxation, on five subjects with normal health and no known cardiovascular disorders. Further correlation coefficients of different parameters have been obtained.

In this exploratory study, there was no selection and classification of subjects. Further the time of the recording and the level of exercise were not controlled. Hence it is pre-mature to draw any specific conclusions from the analyses results.

Some suggestions for future work are:

(i) Recording with classification of subjects according to HR, BP and other known problem, and under controlled condition,

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

References

1. B. Kapke, "Deep listening: revealing the pulse," *Massage & Bodywork Magazine*, pp. 1-6, Nov. 2004.
2. A. Pandey, *Nadirahasya* (Hindi), Varanasi: Medical Pustak Bhavan, pp. 5-22, 1956.
3. P. Pandit, *Nadividnyanam* (Sanskrit with Hindi translation), Varanasi: Chaukhamba Sanskrit Series, pp. 2-35, 1954.
4. A. Surve, "Analysis of radial arterial pulse waveform," M.Tech. dissertation, Supervisor: Prof. P.C. Pandey, EE Dept., IIT Bombay, Jan 2004.
5. S. Upadhyay, *Nadi Vijnana* (*Ancient Pulse Science*), Varanasi: Chaukhamba Sanskrit Series, pp. 162-163, 1986.
6. "Dudgeon's sphygmograph," website of University of Iowa Health Care, Iowa City, Iowa, http://www.uihealthcare.com/depts/medmuseum/gallaeryexhibits/beatgoesonhistory/02bloodpressre.html, accessed in 2004.
7. J. Webster, *Encyclopedia of Medical Devices and Instrumentation*, New York: Wiley, pp. 2770-2776, 1988.
8. M. Dasrao, Y. Hock, and E. Sim, "Diagnostic blood pressure wave analysis and ambulatory monitoring using a novel, non-invasive portal device," *Proceedings of International Conf. on Biomedical Engineering Biovision 2001*, pp. 267-272, 2001.
9. "MediWatch," website of HealthSTATS International Pvt. Ltd, Singapore, http:// www.heathstats.com.sg, accessed in 2004.
10. "Arterial Tonometry," website of Colin Europe, Courbevoie, France, http:// www. colin-europe.com/pages/tonometry.html, accessed in 2004.
11. W. Binghe and X. Jinglin, "Detecting system and power-spectral analysis of pulse signals of human body," *Proceedings of International Conf. on Signal Processing*, Beijing, China, pp. 1646-1649, 1998.
12. J. Lee, M. Jeong, and S. Hwang, "Development of a radial artery pulse wave transducer for diagnosis of human body constitution," *Proceedings of ISR*, pp. 19-21, 2004.

13. “Piezoelectric transducer,” website of Iowa state university, Ames, http:// www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/ EquipmentTrans/piezotransducers.htm, accessed in 2005.
14. J. Hampton, *The ECG Made Easy*, Singapore: Longman Singapore, pp. 1-19, 1996.
15. J. Webster, *Medical Instrumentation,* Noida: Gopsons Papers, pp. 139-149, 1998.
16. J. Webster, *Encyclopedia of Medical Devices and Instrumentation*, New York: Wiley, pp. 2265-2269, 1988.
17. M. Palhang, and E. Zahedi, “Intelligent sensor for a photoplethysmograph using virtual instrumentation," *Proc. IEEE Asian-Pacific Conf. Biomedical Engineering*, pp. 322 - 323, 20-22 Oct. 2004.
18. V. Pandey, "Signal processing for impedance cardiography," Supervisor: P. C. Pandey, *Ph. D. IInd Progress Report*, Biomedical Engg., IIT Bombay, Aug. 2004.
19. A. Oppenheim, and R. Schafer, *Discrete-Time Siganl Processing*, Delhi: Prentice-Hall, pp. 694-703, 2001.
20. J. Proakis and D. Manolakis, *Digital Signal Processing*: *Principles, Algorithms and Applications,* New Delhi: Prentice-Hall, pp. 120-121, 2000.
21. V. Pandey and P.C. Pandey, “Improved Detection of Ventricular Ejection Time for Impedance Cardiography”, *Proceedings of Indian Conf. on Medical Informatics and Telemedicine,* Kharagpur, India, pp.146-150, Feb. 2005.
22. W. Daniel, *Biostatistics: A Foundation for Analysis in the Health Science*, Kundli: Replica Press Pvt. Ltd., pp. 432-434, 1998.
23. R. Rummel, “Understanding correlation,” *lecture notes*, University of Hawaii, Honolulu, http://www.mega.nu:8080/ampp/rummel/uc.htm#C1, accessed on 2005.