DEVELOPMENT OF DATA ACQUISITION SYSTEM AND ANALYSIS OF HUMAN PULSE FOR *VATA*, *PITTA* AND *KAPHA* DOMINANCE IN *PRAKRUTI*

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DOCTOR IN PHILOSOPHY (Ph.D.)
IN
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BY
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UNDER THE GUIDANCE OF

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CERTIFICATE

This is to certify that the work incorporated in the present thesis entitled "**Development of Data Acquisition System and Analysis of Human Pulse for V*ata*, *Pitta* and *Kapha* Dominance in *Prakruti*.**" submitted by **Kalange Ashok Ekanath** was carried out under our guidance at Department of Electronic Science, University of Pune. The work in this thesis is original and has not been previously reported or submitted for the award of any degree, diploma, fellowship or any other university or institution of higher learning. Any relevant material that has been obtained from the other sources has been duly acknowledged in this thesis.

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DECLARATION

This is to certify that the work incorporated in the present thesis entitled "**Development of Data Acquisition System and Analysis of Human Pulse for V*ata, Pitta* and *Kapha* Dominance in *Prakruti*.**" submitted by **Kalange Ashok Ekanath** was carried out under the guidance of Dr. (Ms.) S. A. Gangal at Department of Electronic Science, University of Pune. The work in this thesis is original and has not been previously reported or submitted for the award of any degree, diploma, fellowship or any other university or institution of higher learning. Any relevant material that has been obtained from the other sources has been duly acknowledged in this thesis.

Ashok E. Kalange

Place: PUNE.

Date: May 2011.

I, very humbly, dedicate this work to my father Ekanath Kalange, my mother Hirabai Kalange and to my brother Late Suresh Kalange, who have been a great source of inspiration not only for me but to each and every member of my family.

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Abstract

Ayurveda is a Sanskrit word that translates into knowledge (*Veda*) of life (*ayur*). Diagnosis, according to *Ayurveda,* is to find the root cause of a disease. Out of the eight different kinds of examinations *nadi-pariksha* (pulse examination) is important. *Nadipariksha* is done at the root of the thumb by examining the radial artery using three fingers. By examining the pulse, an *Ayurvedic* physician finds the predominant *dosha* out of the three - *Vata*, *Pitta* and *Kapha*. These three act as basic constituents and protective barriers for the human body in its normal physiological condition. When out of balance, these cause the disease. Once it is known which *dosha* is aggravated or out of balance, it is easy to bring it under control or balance using different kinds of therapies. An expert *Nadi-Vaidya* diagnoses the disease quite accurately. Presently, this technique is subjective and the accuracy of the diagnosis depends upon the expertise of the *Ayurvedic* physician. It was felt that the method be converted to the objective one. With this view, in the present work human pulse data acquisition system is developed using commercially available piezoelectric pressure sensors. The system is validated using the commercially available similar system. The data is collected from large number of subjects and is analyzed using various techniques for *Vata, Pitta* and *Kapha* dominance in *prakruti.*

The thesis is comprises three chapters.

Chapter 1 introduces the topic of research with the necessary background. It then describes the *Ayurvedic* and modern view of radial pulse. A comprehensive literature survey of the work being carried out in India and abroad on radial pulse detection and analysis for disease diagnosis is presented in it. It also gives a review of the commercially available human pulse acquisition systems which are used for pulse sensing especially by western and traditional Chinese medicine system. The Chinese practitioners use the systems during acupuncture treatment and disease diagnosis by traditional way with pulse detected at six different points on both the hands. Western systems are used for clinical purposes e.g. for arterial elasticity, augmentation index measurement etc. As against Chinese method ,the indian *Ayurvedic* diagnosis is based on pulse (*Nadi*) examination at three points on the wrist of either left (in case of female) or right (in case of men) hand. The system is, therefore, to be developed keeping this

difference in mind. Accordingly the objectives of the work are decided and spelt out at the end of chapter 1.

Chapters 2 explains the experiments carried out for the development of data acquisition system to make the subjective method of radial pulse diagnosis into an objective method. The chapter reports the development of four radial pulse data acquisition systems using Digital storage Oscilloscope (for single pulse point), NI PCI 6259 DAQ Card (for single pulse point), NI USB 6008 (for three pulse point), and DAQ card and Microcontroller (89C51RD2) based (single pulse point).

All the four systems are successfully developed and showed the feasibility of using them for radial pulse acquisition. The hardware designed and developed for sensor interface and sensor signal conditioning is described in this chapter. The data is acquired with the help of PCI card and USB interface and it is displayed on PC screen and stored for offline analysis. The results obtained are as good as those of commercially available radial pulse acquisition system (power lab 4/30).

Out of these four, the three pulse point examination system- named as "*Nadi Parikshan Yantra*"-was used for pulse data collection and analysis. The system is validated by comparing the same with data collected using commercially available system. After successful development of "*Nadi Parikshan Yantra*" it was used for collecting the radial pulse data of large number of subjects.

Chapter 3 in the beginning describes the guidelines for data collection. The data is collected from single dominant *(Pradhan*) *dosha* point and all three *dosha* points. The same subjects were examined by Ayurvedic Physician (*Nadi Vaidya*) and the pradhan *Dosha – Vata, Pitta or Kapha* – was identified. Correlation was established between the two with a view to use the electrical pulse data only for identifying the *pradhan dosha* of the subject. The radial pulse data collected was analyzed in frequency and time domains. The results obtained are compared with the results available in the literature.

The data of 100 subjects by single point measurement and 120 subjects by three point measurement was collected. The analysis of collected pulse data is done with the help of Lab VIEW and Origin lab software. The acquired data was also analyzed in Frequency domain for pulse rate, pulse rate variability and amplitude ratio of harmonic frequency components. The results obtained are presented and interpreted for *Vata,* *Pitta* and *Kapha:* pradhan *doshas*. The acquired pulse data is analyzed in time domain for the ratios of amplitude of two waves as well as their respective times. The analysis of radial pulse data is done on the pulse shape. Finally thee point pulse data is correlated with the Nadi-Vaidya's prediction for pradhan dosha on the basis of amplitude of pulses. The results are also compared with the ones available in the literature. To the best of authors knowledge, this type of analysis is reported for the first time.

At the end of the thesis the future plans are proposed. With the encouraging results obtained, it is planned for collection of large data, analysis of the same in all respects and tune the system for disease diagnosis (*Nadi-Pariksha*). The commercially available sensors used for pulse detection have either large size or inadequate frequency response. It is therefore planned to modify the pulse sensor. It is also planned to simulate the Nadi-Vaidya's fingers using artificial (robotic) fingers and flexible sensors.

To overcome the poor frequency response of the ultrasonic sensors, there is necessity of piezoelectric pulse sensor with small diameter (10-12 mm) and the frequency response suitable for pulse detection. Therefore it is planned to develop such sensors. To be used with developed system for human pulse data collection and the performance will be validated. Further, the data will be analyzed for using various pulse analysis systems for their possible use in disease diagnosis.

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CHAPTER 1

INTRODUCTION

AND

LITERATURE SURVEY

1.0 Background

A*yurveda*, the ancient Indian medical science, despite its comprehensive foundation, has not received the due scientific recognition in modern times, largely because of the lack of a quantitative basis for experimental research in its traditional practices. Today, whenthe growing need for efficient alternatives to the modern medical system is felt to fill in the gaps of the modern sciences of health care, research in *Ayurveda*, as well as other traditional medical sciences, is getting a new thrust.

PrakrutiNidana, the basis of diagnosis and treatment under Ayurveda, describes one's natural constitution (*prakruti*) in terms of three basic principles *vata*, *pitta*, and *kapha*, collectively called the *tridosha*. Ether (space), Air, Fire, Water and Earth, are the five basic elements in human body, the combination of which manifest *tridosha*(1)*.* From the Ether and Air elements, the bodily air principle called *Vata*is manifested. The Fire and Water elements exist together as the fire principle called *Pitta.* The Earth and Water elements exhibit as the water principle, *Kapha.* In thephysical body*, Vata*is thesubtle energy of movement; *Pitta* is the energy of digestion and metabolism, whereas *Kapha*is the energy that forms structure of the body. These three *doshas*determine individual's constitution and govern functions of the body in normal conditions and when out of balance, they contribute to the disease process.

Diagnosis according to *Ayurveda,*is to find the root cause of a disease. Out of the eight different kinds of examinations *Nadi-Pariksha*(pulse examination) is very important. *Nadi-pariksha*is done at the root of the thumb byexamining the radial artery using three fingers. The radial pulse is usually chosen as the site to read the *Nadi* (pulse) because it is more convenient to read and is more readily available than other pulse sites.*Ayurveda* and Traditional Chinese Medicine use the pulse pressure signals which are observed over radial artery, at the wrist, for identification of health status of the human being. The features associated with the pulse pressure signals are important from diagnostic point of view. Ancient *Ayurveda* identifies the health status by observing the wrist pulses in terms of '*Vata', 'Pitta'* and '*Kapha'* as the basic elements of human body and in their combinations. They are further substantiated by their *gati, bal, taal etc.* Similarly Traditional Chinese Medicine classifies the pulse based on the pulse characteristics like force, rate, rhythm, volume, regularity and contact pressure required to observe the pulse. Pulse is also classified as fast or slow, tense or tender, floating or sinking, large or small, empty or full, etc., with each term reflecting a personal constituent or condition of the body.

Diagnosis by traditional pulse analysis – *Nadi-Pariksha*- requires a long experience in pulse examination and a high level of skill. The interpretation tends to be subjective, depending on the practitioner. Thus it is advisable to develop a data acquisition system which is objective and can be used in Indian Medical system for disease diagnosis. Many scientists have made and are making efforts to make the *Nadi*diagnosis objective and more accurate. Present thesis is an attempt in the same direction. Some of the basics relevant to the present thesis of radial pulse in Ayurvedic way and in modern way are given in the following article.

1.1 The radial pulse: Ayurvedic View

NadiPariksha (Pulse examination) is done by feeling the pulse at three points on the radial artery by using three fingers. The three points on the wrist indicating the positions of three *doshas* are shown in Fig.1.1.

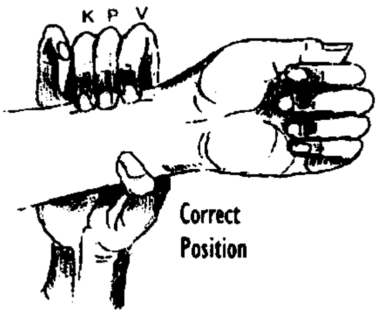


Fig.1.1 Position of three *doshas*(1)

Vata pulse is best felt under the index finger. *Vata*pulse is superficial, cold, light, thin, feeble and empty. With more pressure, it disappears. It moves fast and may become irregular. With keen observation one can feel a little leech or a little cobra moving under the finger. *Vata*pulse is cold to the touch.

Pitta pulse is best felt under the middle finger.*Pitta* pulse is full with a strong throb. It is hot and abrupt, with high amplitude, good volume and considerable force. It moves like a leaping frog. It is hot to the touch.

Kapha pulse is felt at proximal finger. It is deep, slow, watery, wavy and cool to the touch. It moves like a swimming swan. The typical *gati's* of the Nadi(Radial pulse) are shown in fig.1.2(1,2). Other characteristics of the pulse are given in Table 1.1

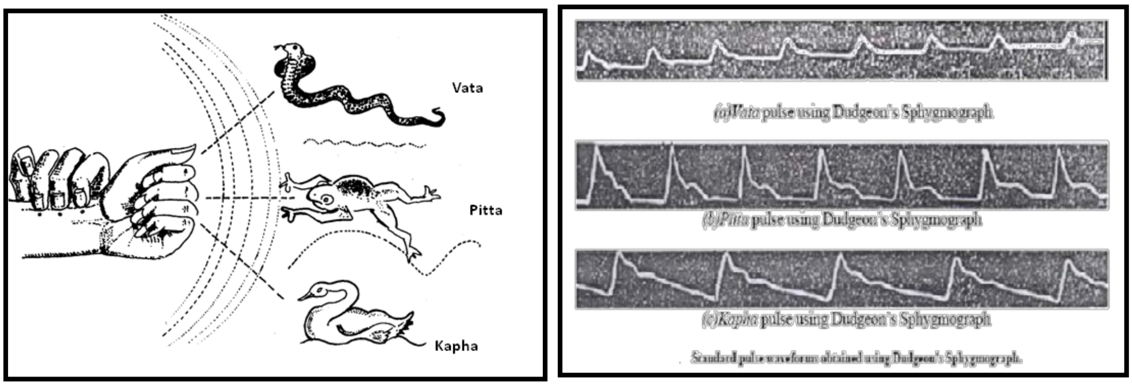


Fig.1.2 Three basic *gatis* of *Nadis*

Table 1.1: Characteristics of pulse (1)

	VATA	***PITTA***	***KAPHA***
Gati(Movement)	*Sarpa* (cobra)	*Manduka* (frog)	*Hansa*(swan)
Vega(Rate)	80-95	70-80	50-60
Tala(Rhythm)	irregular	regular	regular
Bala(Force)	low	high	moderate
Akruti(Tension and Volume)	low	high	moderate
Tapamana (Temperature)	cold	hot	warm to cool

1.2 The Radial pulse: Modern View

Radialpulse is defined as the rhythmic expansion of arterial wall due to the transmission of pressure waves along the wall of arteries that are produced during each systole of the heart(3). The radial pulse is periodic fluctuation that is caused by the heart and occurs at the same frequency as the heart beat. The radial pulse perceived by a clinician is the *pressure* pulse in a large, accessible artery.

A typical pressure wave is shown in Fig.1.3.Generally, there are two main components of this wave: forward moving wave and a reflected wave (3,4). The forward wave is generated when the heart (ventricles) contracts during systole.The wave before dicrotic notch reflects the heart systole; the wave after the notch reflects the diastole. Peak1 and peak2 are the percussion wave and dicrotic wave of pulse respectively. The parameters H1, H2 and H3 are the heights of peak 1, valley and peak2 in pulse respectively. The parameters t1, t2 and t3 are their corresponding time values. W1 and W2 are their widths at the heights 0.9 times of H1 and H2 respectively.

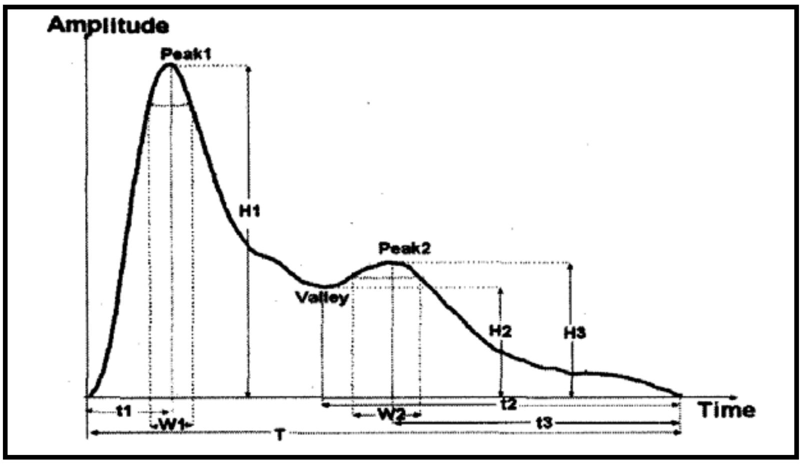


Fig1.3: Schematic figure of pulse parameters

Analysis of the pulse can be done in Frequency domain, time domain or mixed domain. Time-domain parameters of pulse signal used by scientists during analysis are shown in Fig. 1.3(4, 5).In frequency domain the harmonic components of the radial pulseare calculated and their ratios are used for analysis.

1.3Literature Survey

The pulse diagnosis is one of the most important examinations in Ancient *Ayurveda*Medicine (AAM)and Traditional Chinese Medicine (TCM). Large number of research papers are available in the literature based on TCM. The number is comparatively less in case of AAM. In TCM disease diagnosis is based on the pulse pressure observed at six radial points -

threeon left wrist and three on right wrist. In AAM diagnosis is done with the help of the information obtained from the three pressure points on either left wrist (in case of men) or on right wrist (in case of women). Some of the researchers have reported development of the pulse data acquisition systems and have used the data collected for analysis. Some commercial equipment which helppulse diagnosis are available. Researchers have collected the radial pulse data either by using the equipment developed by them or using the commercially available equipment. Various statistical methods and mathematical models are used for analyzing and interpreting the radial pulse data. The research papers and the equipment relevant to the scope of the present work are reviewed in this article.

Upadhyaya(2) used Dudgeon's sphygmogram for radial pulse sensing and quantitative measurements. The pulse data obtained from a large number of subjects as well as patients at different times during the day was used. The analysis of pulse waveform involved the study of following parameters: 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 (due to the rate of contraction of left ventricle), angle of deviation of percussion wave and distance of dichrotic notch from the base line.

Upadhyaya studied the above parameters for pulse wave with the three *doshas.*He recorded the pulse waveforms of *Vata, Pitta* and *Kaphadosha* respectively. Table 1.2 shows the measurements of parameters corresponding to *Vata, Pitta* and *Kapha*pulses of sample recording.

Table 1.2: Measurement of parameters corresponding to Vata, Pitta and Kapha pulses. (reproduced from (2))

Type of pulse	Pulse period (S)	Length of percussion wave (cm)	Time of percussion wave (S)	Angle of deviation (^{0})	Distance of dicrotic notch (cm)
Vata	0.73	0.40	0.21	65^0	0.15
Pitta	0.81	1.40	0.76	81^0 48’	0.80
Kapha	0.94	0.62	0.27	77^0 30’	0.30

Upadhaya reported that the *vata*pulse takes minimum pulse period and has smallest length 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 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.

Lee and Wei (6) analyzed the spectrum of pulse at radial artery at wrist and correlated its spectral features with health condition of the subject. In traditional Chinese medicine, pulse is sensed at three different points, Cun, Guan and Chi, along the radial artery on the wrist of both hands. By applying maximum and minimum pressure at these points, physician detects the condition of the internal organs of the patient. By keeping the condenser microphone (“Bruen&Kjar 4147”) at *Cun*and *Guan* positions using approximately minimum and maximum pressure the analog waveforms of pulse were sensed at both the wrists. The recording of pulse at *Chi* position was avoided in order to prevent inconvenience to patient by applying pressure to three close points for long duration. The waveforms were digitized for their use in spectral analysis in terms of spectral energy ratio (SER).

SER is defined as the ratio of the energy of pulse spectral graph (PSG) below 10 Hz to that above 10Hz. The pulse signal is present in the range of 0 to 25 Hz and decreases gradually. However Lee and Wei measured the energy from 1 to 50 Hz, assuming the signal below 1 Hz to be due to motion artifact.

The power spectra at eight different points are approximately coinciding with each other. It indicates the pulse waveforms taken from all positions are almost similar for normal person. The SER values calculated for large number of normal subjects showed that maximum energy of pulse signal is concentrated below 10 Hz.

B. H. Wang et al (7) have used the microphone based pulse detecting system for sensing radial pulse at wrist and analyzed the power spectra of four types - normal, smooth, wiry and slow–intermittent – of pulses according to traditional Chinese medicine system. The power spectra of the four kinds of pulse signals are obtained by using the Fast Fourier Transform (FFT) and the power-spectral characteristics are analyzed and compared. The pulse signal was low pass filtered with the cutoff frequency 50 Hz. Further analog pulse signal was digitized by using sampling frequency f_x of 128 Sa/s with a sampling length T of 16 s.

Following are the characteristics of power spectra reported by the author. Power spectra of the normal pulse signal distribute within 25Hz, with the envelope decreasing with increase in frequency. Smooth pulse has over 10 harmonics, normal pulse has about 8, wiry and intermittent pulse have 3-5 harmonics components. The breathing frequency was found around 0.2-0.5 Hz and it is different for different subjects. It was found that the spectral energy of pulse is approximately concentrated below 10 Hz.

Yoon et al (8) proposed a new quantification scheme of specific pulse characteristics.The characteristics were determined using the pressure-adjusting pulse detector, the authors previously developed. Sensor was kept over a pulse point and contact pressure was regulated by varying number of weights (20 g each).Amplitude of the pulse is recorded. Authors used following three characteristics for the quantification of the traditional pulse type classification - (a) The contact pressure at which the maximum amplitude is attained (degree of pulse floating) (b) The height of the maximum amplitude (degree of pulse size)(c) The width of the contact pressure between the two points in the curve at which 80% of the maximum amplitude is attained (degree of pulse strength).

Authors collected data of 33 healthy subjects (both male and female) in the age range 21 to 41 years atleft radial artery. The contact pressure exerted on the pulse point was increased in increments of 4 kPa, going from 4 kPa to136 kPa. At each level of applied pressure, local maxima and local minima amplitudes were extracted and the pulse amplitude was calculated taking the difference between them. They observed common feature for each subject that amplitude of the pressure waveform first increases, reaching a maximum, and decreases when the contact pressure is continuously increased. It is also observed that there are different pulse patterns(waveforms) for different subjects, for each of the three pulse characteristics.

The degree of pulse floating is measured by the first contact pressure at which the maximum average amplitude of the pulse signal appears. The degree of pulse size is defined as the maximum average amplitude, and the degree of pulse strength is defined as the range of pressures where the average pulse amplitude is above 80% of the maximum value.

Through the data collected the authors introduced numerical scales to the degrees of the floating, the size, and the strength of the pulse. They computed the correlations among them. The value of the correlation between the pulse floating and the pulse size,C_{fl-sz}, was 0.07. For the correlation between the pulse size and the pulse strength, C_{sz-st}, and that between the pulse strength and the pulse floating,C_{st-fl}, they obtained 0.24 and 0.60. Authorshope to apply this analysis process for diagnostic purposes.

Lau et al (9) studied the relationship between wrist-pulse characteristics and body conditions based on the empirical study of radial pulse contours. They enrolled 30 normal, 30 with heart-problem and 30 with chronic renal failure subjects for this study. Radial pulse waves were measured non-invasively from the Cun, Guan and Chi positions in TCM (*vata ,pitta* and *kapha* positions respectively in Ayurveda) on the left hand. Pressure sensor type PSS-02KAF (from Kyowa Electronic Instrument Co. Ltd. Japan) was used. It was fixed onto a wrist-watch-like structure to place the sensor accurately over the radial artery.

A children-size sphygmomanometer cuff was wrapped around the wrist-watch-like structure and used to produce the hold down pressure. The cuff was first inflated to a pressure at which the pulse wave starts to appear on the monitor screen. After the pulses were recorded for about 15 seconds, the cuff was further inflated to a level at which pulses become bigger and clearer for the second recording. The procedure was continued until the pulse amplitude start to diminish. The pulse waves were sampled at rate of 100 Hz by a 12-bit analog-to-digital converter for storage onto a personal computer.

Data selection criterion used was to seek a series with clear contour of relatively large amplitude. Three series were selected from left Cun, Guan and Chi positions. An ensemble averaged pulse was computed from each selected series. The contour characteristics of each pulse was studied and classified. The study showed the effects of heart and kidney problems on pulse contour. Authors showed that the pulses in the heart-problem group had 4 general contour characteristics and those in the renal failure group have 5.

Bhattacharya et al (10) used photoplethysmograph as a noninvasive device for detecting blood volume changes by optical means. The data was collected for qualitative assessment of the overall clinical status of the subject and characterization of complex cardiovascular dynamics from digital blood volume pulsations. The detection and the extraction of periodic component were performed with moving window to accommodate the variations of the physiological oscillations. The covariance matrix formed by the gradually varying pattern was used as a simple measure of qualitative assessment. Further, the characterization of the underlying system in the light of nonlinear dynamical analysis was also presented. The stable subjects were shown to behave as a low-dimensional system whereas the diseased subjects exhibited comparatively high dimensional activity.

Munet al (11) investigated the change in the radial arterial pulse during Cold Pressure Test (CPT). They found that the pulse wave form changed consistently for all the 32 subjects. The pulse detector system was composed of a piezoelectric pressure sensor with signal preampliers, a filter and an A/D converter. The pressure sensor (MPX-2300DT1) was attached on the left radial artery and the signal was delivered into the signal conditioner (SCXI 1125).

The signal after the conditioner enters the PC and can be seen real time. Authors measured the arterial pulse, while the subject was seated on a chair. Then subject’s right hand was immersed in the 10°C water for five minutes while the room temperature was 22°C. Thirdly, the hand was taken out of water, dried, and kept in the air without covering for five minutes. During each of these three experiments the pulse data was collected continuously for five minutes.

Millasseau et al (12) worked on the determination of age related increase in large artery stiffness by digital pulse contour analysis. Aging is accompanied by increased stiffness of large elastic arteries leading to an increased in pulse wave velocity (PWV). Further the PWV may also influence the contour of the peripheral pulse, suggesting that contour analysis might be used to assess large artery stiffness. Authors have previously demonstrated that contour of the digital volume pulse (DVP) contains similar information to that of peripheral pressure pulse. The contour of DVP is formed as a result of complex interaction between the left ventricle and the systematic circulation.

An index of the large artery stiffness (SI_{DVP}) was derived from the digital volume pulse (DVP). DVP was measured using photoplethysomgraph by transmitting IR light at 940 nm placed on index finger of the right hand. DVP waveforms were recorded over 10 sec and ensemble averaged to obtain a single waveform from which ΔT_{DVP} was determined as the time between first systolic peak and early diastolic peak. $SI_{DVP} = h/ \Delta T_{DVP}$ where, h is the height of the subject. PWV was determined by measuring the carotid- to-femoral transit time.

SI_{DVP} was compared with PWV_{cf} obtained by applanation tonometry in 87 asymptomatic subjects (21±68 year's 29 women). The reproducibility of SI_{DVP} and PWV_{cf} and the response of SI_{DVP} to glyceryltrinitrate were assessed in subsets of subjects. The mean within-subject coefficient of variation of SI_{DVP}, for measurements at weekly intervals, was 9.6%. SI_{DVP} was correlated with PWV_{cf}. SI_{DVP} and PWV_{cf} were each independently correlated with age and mean arterial blood pressure (MAP) with similar regression coefficients.

Administration of glyceryltrinitrate (3, 30 and 300 µg/min intravenous, each dose for 15 min) in nine healthy men produced similar changes in SI_{DVP} and PWVcf. Thus contour analysis of the DVP provides a simple, reproducible, non-invasive measure of large artery stiffness.

Manning et.al.(13) assessed the impact of the measurement site (lower versus upper extremity) on the corresponding compliance variables and the overall reliability of diastolic pulse contour (Windkessel-derived) analysis in normal and hypertensive subjects using arterial tonograms. Arterial tonograms were recorded in the supine position from the radial and posterior tibial arteries in 20 normotensive (116±12/68±8 mm of Hg) and 27 essential hypertensive subjects (160±16/94±14 mm of Hg). Ensemble-averaged data for each subject were fitted to a first-order lumped-parameter model (basic Windkessel) to compute whole-body arterial compliance (CA) and to a third-order lumped-parameter model (modified Windkessel) to compute proximal compliance (C1) and distal compliance (C2).

Despite high-fidelity waveforms in each subject, the first-order Windkessel model did not yield interpretable (positive) values for CA in 50% of normotensives and 41% of hypertensives, whereas the third-order model failed to yield interpretable C1 or C2 results in 15% of normotensives and 41% of hypertensives. No between-site correlations were found for the first-order time constant, 2 of the 3 third-order model curve-fitting constants, or CA, C1, or C2 ($P>0.50$). Mean values for all 3 compliance variables were higher for the leg than the arm ($P<0.05$ each).

Authors concluded that differences in Windkessel-derived compliance values in the arm and leg invalidate whole-body model assumptions and suggested a strong influence of regional circulatory properties. The validity and utility of Windkessel-derived variables was further diminished by the absence of between-site correlations and the common occurrence of uninterpretable values in hypertensive subjects.

Hlimonenko, et al (14)studied the elastic properties of vascular tree noninvasively in human subjects as a function of aging using the shape of peripheral (radial) pulse wave. They used 21 subjects in two age groups, 22-30 and 37-72 years. The special laboratory instrument for photoplethysmographic (PPG) signal amplification was used. For photoplethysmographic (PPG) measurements the finger clip sensor (From NellcorDurasensor Analog) was used. National Instruments data acquisition board (DAQ) was used to digitize the signals and transmit the digital data to the personal computer. The waveforms were analyzed offline using Lab VIEW programs. They observed that the peripheral pulse has a steep rise and a dicrotic notch on the falling slope in the younger subjects. With older subjects a more gradual rise and fall and no pronounced dicrotic notch were observed. Various parameters used for analysis are defined the PPG pulse shown in Fig 1.4

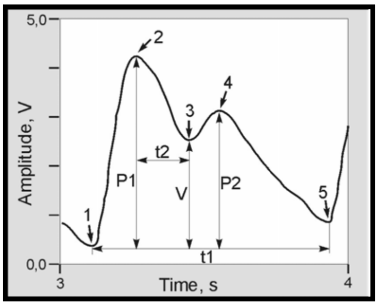


Fig.1.4: PPG signal pulse (11)

The analyzing program calculated ratios t2/t1, P2/P1 and V/P1. It was found that the ratio t2/t1 decreases with age. For the subjects in the age group of 20-30 years, the ratio t2/t1 remains nearly 0.15-0.25, except one subject. With the decrease in age, the t2/t1 starts to decrease to nearly 0.11. The ratio V/P1increases with age and the ratio P2/P1 do not depend on the age. Differences in the ratios P2/P1, t2/t1 and V/P1 between age groups were compared by the authors using the statistical program ANOVA.

Results shows that the two ratios t2/t1 and V/P1 were significantly different in terms of statistics at $p<0.05$. Authors concluded that ratios t2/t1 and V/P1can be used to analyze distensibility of arteries. The decrease in the ratio t2/t1 occurs with an increase in the age. The smaller this number, the stiffer arteries are. The increase of ratio V/P1 happens with increase of age. The greater is this number, the stiffer the arteries are.

Authors found that the position of the second peak of the pulse depends on the age of the subjects. This is attributed to the increase in aortic stiffness and pulse wave velocity. As the vessel gets stiffer during aging process, the reflected wave returns faster and due to the summation of waves the resultant pulse wave changes.

Experiments on evaluation of herbal formulas by pulse analysis method were carried out by Wang et. al(15). Thirty-five rats were used for each formula set. Blood pressure pulse of the tail artery was obtained through the transducer. The rat was then fed with the liquefied herbal formula and the post-treatment recordings of pressure pulse were taken every 2 min for 3 h or more.

Authors collected data on the harmonic properties of radial before and after the herbal treatments. They used this information on variation of Fourier components to quantify the effect of herbal treatment. It is known that the physical condition of organ or tissue are related to specific Fourier components of the blood pressure pulse via their influence on the blood pressure wave propagation and thus blood distribution to the body. Authors have cited a large number of research papers in support of this theory.

The herbs selected were found to have specific effects on the Fourier components of the blood pressure pulse. Authors concluded that the component adjustment of an herbal formula could be distinctly and quantitatively detected by pulse analysis method. They have further reported that the pulse analysis method can quantify the herbal effect and is closely related to fundamental Chinese medical theory. It helps herbal formulation to be much reasonable and easier and makes the evaluation of clinical Chinese medicine therapy possible.

McLaughlin et al (16) developed a fast and easy to use system for the determination of peripheral arterial pulse wave velocity (APWV). They report this to be a reliable and reproducible non-invasive method of measuring peripheral arterial pressure pulse wave velocity in humans. APWV is a measure of the elasticity (or stiffness) of peripheral arterial blood vessels. The pressure pulse velocity varies over the range from about 12 to15 ms^{-1} in stiff peripheral arteries, whereas in normal arteries it is in the range of 7 to 9 ms^{-1}.

Two PVDF sensors were placed, one on the radial artery at the wrist and the second on branchial artery just above the elbow-using elastic bandage. The measurement system developed by authors consisted of a charge amplifier, signal amplifier, noise filter, A/D converter and data acquisition module. Data acquisition and analysis was carried out using Lab VIEW. An analysis program was developed which filters the measured data and calculates the arterial pulse wave velocity using three different methods: peak-to-peak detection, cross-correlation and foot-to-foot detection. The mean of all three results is taken as the most representative of the true pulse wave velocity. The values obtained are a little higher, but similar to values published in the literature.

Authors reported that the clinical usefulness of the instrument lies in the conversion of the velocity values to values of local stiffness (elasticity) of peripheral arterial walls. Patients with peripheral arterial disease, pre- and post-surgery patients (for example, bypass of superficial femoral block) and pre- and post-treatment patients (for example, urokinase for anterior tibial block) will be obvious beneficiaries of this non-invasive technique. Authors plan to convert this data into arterial stiffness for their clinical use

Wang et al (17) proposed an improved Dynamic Time Warping (DTW) algorithm to recognize pulse waveform. Among the 27pulse patterns of Traditional Chinese Pulse Diagnosis, unsmooth pulse, taut pulse, moderate pulse, smooth pulse and hollow pulse are the pulses distinguished in shape. Author reported that these pulses were recognized using DTW algorithm. Extensive experiments on 1,000 pulse waveforms demonstrate that their algorithm had a 92.3% agreement rate with experts.

Mental stress testing is considered a reliable method for diagnosing patients with coronary heart disease (CHD) which may be at risk for future events. It has been shown that myocardial ischemia induced during mental stress tests is specifically associated with peripheral arterial vasoconstriction. A Pilot Study is reported by Gooret al (18) using Peripheral Arterial Tonometry (PAT) technique. The study was undertaken to test the diagnostic capability of PAT to detect peripheral arterial vasomotor changes.

Authors monitored pulsatile finger blood volume changes using a specially designed finger plethysmographPAT that can detect peripheral arterial vasomotor changes. Equilibrium dionuclide angiography (ERNA) was simultaneously performed in 18 male patients at rest and during a mental arithmetic stress test with harassment. From the results obtained, it was concluded that the use of PAT may facilitate both clinical testing and research during mental stress.

Bodlaj et al (19) used applation tonometry technique for collecting the arterial pressure waveforms. The principle of measurement was based on recording the waveform of peripheral arterial pulse pressure at one site and its derivation at another site. The waveform is a result of incident (anterograde) and reflected (retrograde) pressure waves. Study was carried out on 26 healthy adult male professionals, including medical students, aged 21 to 35 years. Ascending aerotic pressures, aerotic augmentation index (AIx), subendocardial viability ratio (SEVR), ejection duration and endsystolic pressure were derived from the aortic pressure waveform. Authors demonstrated for the first time that arterial stiffness and subendocardial perfusion relative to cardiac workload, as assessed by AIx and SEVR, show diurnal variations in healthy young men. In their study population mean AIx, mean brachial diastolic blood pressure and mean heart rate showed a diurnal pattern, with higher levels in the morning and lower levels at noon and in the afternoon, suggesting that arterial stiffness was physiologically increased in the morning and decreased at later times during the day.

This may point to a morning surge in sympathetic nerve activity which may also affect arterial stiffness and could report from either an endogenous rhythm or increased physical activity. Authors reported that the mean SEVR was significantly lower in morning than at mid day or in the afternoon suggesting that subendocardial perfusion relative to cardial workload can lower in morning than later in the day. These observations will be of value in the application of applanation tonometry in human research. In order to achieve comparable measurements, especially in longitudinal studies, measurements should be made at similar times during the course of a day. Authors claimed that these observations would be useful in studies in healthy individuals in whom novel pharmacological compounds with activity on the vasculature, including the endothelium.

Xuet al (20)have presented a review of recent achievements in quantitative analyses of modern research on Traditional ChinesePulse Diagnosis (TCPD). In order to demystify TCPD and prove its efficiency, some fundamental knowledgesuch as concepts, diagnosis methods, and standard pulse patterns are discussed. Authors have reviewed modern researchon TCPD mainly from 4 aspects: objectification of TCPD, analyses of pulse waveform, research into the mechanismof pulse formation, clinic observations, and comparisons on pulse images. For each of these aspects, generalbackground information and a brief explanation on them are given. It is especially important to distinguishthe pulse images based on Traditional Chinese Medicine (TCM) and the sphygmogram based on Western medicine.Authors have reported single point pulse acquisition system and have collected pulse data. Furthermore, typical pulse waveforms and their results were processed by modern signal processing methods such as cepstrum, Short-TimeFourier transforms (STFT), and wavelet transform Finally, theprosperities and difficultiesof modern research on TCPD are pointed out.

Many researchers have made great efforts in pulse analysis. But the mapping relations between pulse wave and pulse types is not considered, which undoubtedly limits their applications in clinical medicines, Wang and Cheng (21) developed a new quantitative system for pulse diagnosis, in Traditional Chinese Medicine (TCM), 2ased on Bayesian Networks (BNs) to build the mapping from pulse parameters and pulse types. Pulse samples were pressure waves. The pulse sample data base consists of two parts,1) a total of 407 pulse waves collected from 248 patients and 109 healthy volunteers and2) diagnostic results of pulse type. In order to classify pulse types automatically authors developed quantitative system based on BNs to build mapping relationship. The same was interpreted using data from 407 pulse waves. The experimental results validate that the system for pulse diagnosis is effective.

Mahesh et al (22) reported design of a pulse sensor using PVDF material for acquiring the three pulses from th radial artery. They also developed a signal conditioning unit to improve the quality of the signals before they are converted into digital form by the data acquisition card interfacing the computer. The signal conditioning unit designed by authors consists of charge amplifier, voltage amplifier, and a low pass filter. The sensors are firmly held at each of the three radial pulse points - *vata , pitta*, and *kapha* -as identified by *siddha* experts. The pulses are recorded by varying the pressure on the sensor head.Ten healthy subjects in the age group of around 20-30 years with a mean age of around 25 years, who had no history of cardiovascular disease, were selected. Data regarding their daily routine activities and lifestyles which indicate their body type and combination of *doshas*as per the *siddha* concept was also collected through questionnaire. The signal was acquired at rate of 250Hz and the three pulses were recorded one after the other from all the pulse points. The analysis was done offline.

The recording was done three times a day for each subject at the same ambient room temperature, 22-24ºC, during recording.

Authors classified the pulses on the basis of *siddha*theory which states that the three pulses vary in amplitude in the ratios of 1:2:4 for *kapha, pitta*, and *vata*respectively and the frequencies must be 80-95 beats/min for *vata* pulse, 70-80 beats/min for *pitta* pulse and 50-60 beats/min for *kapha* pulse. The frequency analysis of the same subject was done by Authors. They observed from the data that the *vata*pulse rate is less than the normal range that is 80-90 beats/min where as the *pitta* and the *kapha* pulse is within the normal range. They concluded that the person may have less *vata* constituents. Authors also concluded from the amplitude data of the same subjects that the ratio of *vata*, *pitta*, and *kapha* pulses are in the ratios 1: 0.6: 0.4 respectively which indicates that the person is having more *pitta* and *kapha* constituents. They also observed that the pulses are varying over time that is during morning, afternoon and evening.Even though there is variation in the pulse rate of the three pulses and *pitta* pulse is always maintaining higher rate than the other two pulses.

Abhinav et al (23) reported development of 'NadiYantra' to capture the signal from the radial artery. Nadiyantra monitors pressure variation at three close yet precise position of the radial artery. The system comprises of three identical piezo based sensors, amplifier and filter circuits, mechanical set-up and data acquisition system (Bio Pac- 150). Authors report that morphology of the wave form obtained from their system comparewith standard physiological arterial signals. They applied signal processing techniques to obtain morphological features such as amplitude, power spectral density, band power and spectral centroide to reflect the variations in signal from the three channels. Nadiyantra allows recording for hours by an automated external pressure on three positions.

Authors selected five healthy volunteers (subjects) to carry out whole day analysis. They collected 20 sets of signals from same subject over period of time before lunch and were used as control signal. Post lunch signals were recorded and used for analysis. Amplitude of pulse, fast Fourier transforms and power spectrum density (PSW) were taken for analysis. From the results obtained, authors concluded that the system has potential to objectively measure and display the changes occurring in the radial artery in accordance with Ayurvedic principles without having to undergo subjective interpretation.

Joshi et al (24) have reported the development of a system called “NadiTarangini” for acquiring human pulse information for diagnosis purpose. The system contains a diaphragm element equipped with micromachined strain gauge (1cm x 1cm), a transmitter cum amplifier and digitizer for quantifying analog signal. The system is reported to acquire data with 16 bit accuracy with practically no external electronic or interfering noise. Data acquisition card NI USB- 6210 (National Instruments) having an interface with PC was used. The data is captured at sampling rate of 500 Hz. A set of three pressure sensors was used to sense pulses at three locations viz. Vata, Pitta and Kapha.

Authors recorded the waveforms obtained from using *NadiTarangini a*nd reported sample waveforms from the left hand of a patient for *vata*, *pitta* and *kaphadoshas*respectively. They further reported that their recorded waveform consists of important time domain features such as percussion wave (P), tidal wave (T), valley (V) and dicrotic wave (D). Authors also reported that as the contact pressure of the sensor over the pulse point increases, the amplitude of the pulse signal first increases, reaching a maximum, and then decreases. After a particular threshold value, the pulse dies and these observations are consistent with the Ayurvedic literature

Authors studied variation in the pulse waveform with age groups ‘below 25’, ‘25–50’ and ’above 50’. Pulse waveforms obtained are shown to have desirable variables with respect to age of patient and the pressure applied at the sensing element. The waveforms were found to be reproducible and complete. They observed that the ‘below 25’ pulses are more dominant in secondary peaks. ‘25–50’ group is relatively stable, while for people older pulses are irregular in nature. They also mentioned that these findings areonly preliminaryand to investigate further, larger dataset are needed.

Extensive research has been done to show that heart beats are composed of the interaction of many physiological components operating in different time scales with no linear and self regulating nature. More direct and easily accessible manifestation of heart beat is pulse. Joshi et al (25) have established the relevance of the multifractal formation for the artery pulse. The work carried out consists of three parts-

- Authors show that the arterial pulse also exhibits self similar nature and require a large number of exponent to characterize their scaling properties.
- Using wavelet transform they show that the pulse require not one but many exponents to fully characterize the scaling properties.
- They have also shown that the multifractal spectrum vary for pulses from three age groups and two disorders.

The pulse waveforms were recorded using '*NadiTarangani*"(24)and pulse waveform for each volunteer corresponding to three pulse position on two hands were collected. Total waveforms were 108 from 16 volunteers with no heart disorder. Authors looked for variation with age and variation with disorder.They finally reported that further detailed study on larger number of datasets are needed to establish the advantage of the given method compared to other and to find optional combination of methods for diagnostic and prognostic purpose.

Using the equipment 'NadiTarangini' developed in their previous work (24) Joshi et. al. (26) carried out arterial pulse rate variability analysis for diagnosis purpose. Heart rate variability (HRV) has been extensively studied but Joshi et. al. have introduced pulse rate variability analysis on the basis of arterial pulse intervals (API). The pulse cycle consists of Systolic wave (S) and Diastolic wave (D). Authors have extracted API by finding peaks in the S wave. Time domain, Frequency domain and Nonlinear (Poincaré) measures are used for pulse rate variability analysis.

Pulse waveforms were recorded using '*NadiTarangini'* Total of 158 waveforms from 64 volunteers with varying ages and either having a specific disorder or no disorder were used for the study. The measures were used for finding out variations with respect to age similar to previously established results in the domain of HRV analysis. Authors have also computed measures indicating the presence and absence of disorder. Authors' further state that more rigorous studies are needed to determine sensitivity, specificity and predictive value of pulse rate variability in the identification of individuals at risk.

Prasannakelkar et al (27) used pulse waveform obtained using impedance Plethysmography (IPG) for identifying three doshafor disease characterization. IPG was first introduced by Jon Nabber in 1940. Biological tissue and fluids are neither good conductors nor they are bad conductors. The intermediate properties of biological matter make the measurement of electrical conduction through them feasible by simple instruments. The resistance offered by the tissue is called impedance. Measurement of this impedance in various tissues tells about the capacity of electric conduction of that tissue. Small changes in the impedance are caused by physiological processes like blood circulation, respiration etc. Measurement of these physiological processes from the impedance signals is known as Impedance plthysomography, Impedance cardiography or Impedance cardio Vasography.

Electronic division of Bhabha Atomic Research Center (B.A.R.C.) developed first module of IPG in 1978. It has undergone several renovations. During past more than 30 years, the 'variability analyzer system' developed at BARC is used for measuring the variability in heart rate, stroke volume and peripheral blood flow. They have now developed "peripheral pulse Analyzer;" based on IPG. In this system IPG waveform is simultaneously recorded from three different locationscorresponding toVata, Pitta, Kapha locations of Ayurvedic system.

During their studies authors observed that shape or pattern of the peripheral pulse changes significantly in an individual as a function of time. There is marked variation in pulse pattern from subject to subject. Further, pulse amplitude and impedance value varies in disease conditions. It was observed that time interval and amplitude in the different segments of an IPG cycle are directly related to disease condition pertaining to that particular dosha. Above observations were based on the study of 100 subjects and therefore authors state that the observations need revalidation by multicentric trials on large number of subjects in order to use this technique for diagnostic disease characterization.

Same group of scientists in their research paper (28) proposed the application of crisp and fuzzy clustering algorithms under supervised and unsupervised learning scenario for identifying non-trivial regularities and relationships of the radial pulse patterns obtained by using Impedance Plethysmographic technique. The objective was to unearth the hidden patterns to capture the physiological variability from the arterial pulse for clinical analysis, which will provide a very useful tool for disease characterization. Pulse signals from the radial artery were measured using the peripheral pulse analyzer developed at BhabhaAtomicResearch Centre (B.A.R.C), Mumbai, India. The radial artery begins about 1 cm below the bend of the elbow and passes along the radial side of the forearm to the wrist, where its pulsation can be readily felt. With the subject in supine position, carrier electrodes were applied around the upper arm and the palm while sensing electrodes were applied on the distal segment around the wrist. A sinusoidal current of constant amplitude (2mA) was allowed to flow across the wrist of the subject using band electrodes. The amplitude of the signal thus obtained isdirectly proportional to the electrical impedance of the bodysegment. The waveforms obtained were sampled at 100 Hz as atime series data. The data was recorded in normal and diseased subjects for about four minutes on Lab Windows platform. The subjects were in the range of about 18 to 60 years. Approximately 240such samples were obtained from a single subject. Authors tested variety of fuzzy algorithms including Gustafson-kessel (GK) and Gath-Geva(GG) over a diverse group of subjects and over 4855 data sets. About 80% of the patterns were successfully classified. A correlation of patterns with the disease of heart, liver and lungs was judiciously performed

1.4: Review on Commercially Available Instrumentsfor Radial Pulse Acquisition and Analysis.

The instruments/systems available in the market which are used for pulse detection and analysis are: Dudgeon sphygmograph,Arterial Tonometer, COLIN Vascular Profile "VP-1000", Pulse Analysis System (PAS v3.208)Pulse Trace (Micro pulse)andVasotrac. These are reviewed in this article.

1.Dudgeon sphygmograph(29)

In 1882, Dudgeon designed sphygmograph for measuring blood pressure from the radial artery at the wrist. It is a mechanical device which records pulse trace on a piece of smoked paper. Dudgeon sphygmograph is shown in Fig. 1.5.

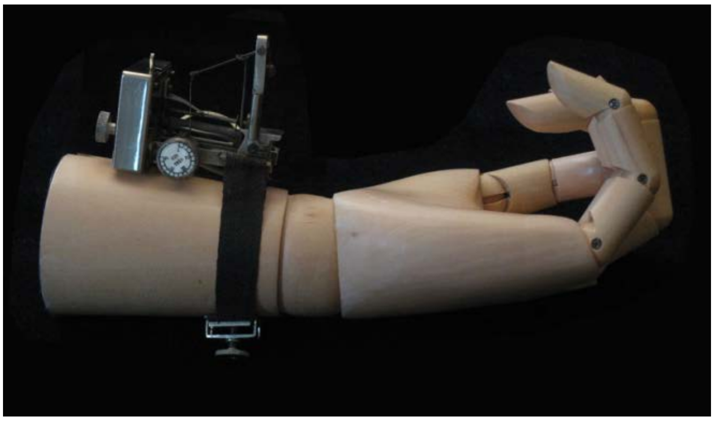


Fig 1.5: Dudgeon sphygmograph

The instrument is equipped with 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. To prepare the instrument for work the key is given full rotation 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 to work, pulleys start rotating the small bar. Thus the smoked paper is moved forward and a pulse tracing is done by means of the hanging needle.

Dudgeon’s sphygmograph was used by Upadhyaya for obtaining pulse tracings and quantitative measurements for pulse classification in accordance with *nadishastra.* Fig. 1.6 shows some sample tracings.

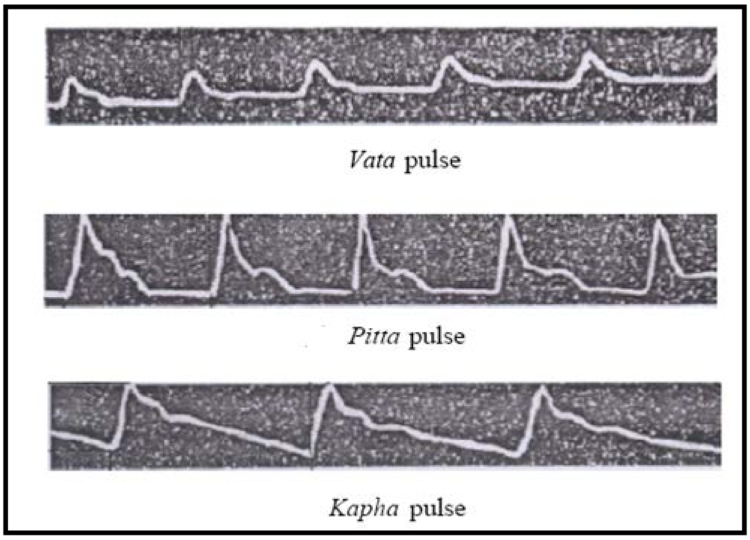


Fig 1.6: Pulse tracings using Dudgeon's sphygmogram as obtained by Upadhyay(2).

The system is bulky and can be used for detecting the pulse at single location at atime.

2. Vascular Profile: (30)

COLIN VP-1000 Vascular Profiler Shown in Fig. 1.7 is fast, fully automated Ankle-Brachial Index (ABI) assessment system. Ankle-Brachial Index (ABI) is the ratio of ankle systolic blood pressure relative to brachial systolic blood pressure.

Fig.1.7: COLIN Vascular Profile "VP-1000"

ABI correlates well with the degree of stenosis in lower extremity arteries, and is widely used to assess peripheral arterial disease (PAD). The VP1000 uses 4 blood pressure cuffs (one on each limb) and highly sensitive electronic pressure transducers to measure veryaccurately the arterial blood pressure and waveform automatically. This giveshighly valuable clinical information within minutes which can aid in the early detection and treatment of arterial disease. The VP-1000 is a powerful screening device for the non-invasive assessment of arteriosclerosis and represents the latest innovation using Colin’s patented “Waveform Analysis and Vascular Evaluation” (WAVE), technology. The VP-1000 assesses arteriosclerosis by Pulse Wave Velocity (PWV) and Ankle Brachial Index: an index to assess arterial occlusion (ABI). The two indices are obtained using simultaneous blood pressure and waveform measurements on all four limbs along with ECG and phonocardiogram tracings. Simple set-up and short operation time make the VP-1000 an ideal tool for patient screening and follow-up. As such it provides benefits for a wide variety of clinical applications related to artery.

3.Pulse Analysis System (PAS v3.208)(31)

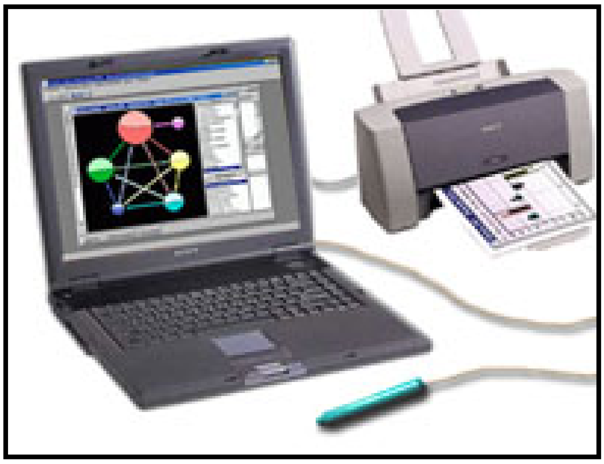


Fig 1.8: Pulse Analysis System (PAS v3.208)

Pulse Analysis System (PAS)(see Fig.1.8) is a commercially available system designed for complete diagnostics of person's health by means of the pulse wave analysis taken of by the special sensor. The result of analysis is a complex estimation of functional systems (Elements, Channels) as a health matrix which reveals all derangement in person's health. The PAS is based on traditional oriental (Chinese) pulse diagnostic and modern data processing methods.

The diagnosis is based on the pulse detected and recorded at six points (three on right hand wrist and three on left hand wrist). The instrument was first introduced in 1988 and the current version of the same is introduced in 2004. The PAS is best used by oriental medicine health centers as a diagnostic tool for acupuncture, herbal therapy and other alternative medicine.

4. Pulse Trace (32)

"Pulse Trace" is a compact desktop unit with a built-in colour monitor and thermal printer. Fig.1.9 shows Pulse Trace equipment manufactured by "Micro pulse".

Fig 1.9: Pulse Trace (Micro pulse)

It provides a complete solution for Pulse Wave Analysis studies, combining sophisticated Digital Volume Pulse (DVP) measurement, with analysis and data management. It uses a high fidelity photo-plethysmography transducer with signal conditioning circuit to obtain an extremely accurate and noise free signal of the DVP waveform.

It is used for rapid non-invasive determination of vascular structure and function. "Pulse Trace" measures Arterial Stiffness Index (SI).This is a known and accepted independent risk factor for major cardiovascular events that can be used to assess cardiovascular health non invasively, identify patients at risk of heart attack and stroke and monitor the progress of vascular disease. Pulse Trace also measures Vascular Tone (RI) providing a simple and non-invasive test of Endothelial Function, an early marker of developing arterial disease, the ability to monitor and diagnose disease processes that modify vascular tone and to monitor effect of specific drug. Key users for this instrument are Hypertension Specialists, Cardiologists, Diabetic Clinics and Diabetolgist, Cardiovascular Drug Trials and epidemiological studies.Hypertension Specialists and Cardiologists with an interest in Hypertension (or Hypertension/Stress Clinics where they exist), for Risk Stratification, early detection of changes in the endothelium, treatment planning and drug studies. Diabetic Clinics and Diabetolgist use this instrument for Monitoring vascular disease, risk stratification, treatment planning and drug studies.

5) Vasotrac(33)

Fig 1.10: Vasotrac

The "Vasotrac" (Manufactured by "Med wave") is an innovative handheld device for monitoring blood pressure non-invasively and accurately. Fig.1.10 shows the photograph of "Vasotrac". It consists of a wrist sensor and a monitor. The wrist sensor is placed over the radial artery at the distal edge of the radius. The position allows the sensor to measure the amplitude of the radial pulse. Analysis of waveshape, form and orher characteristics is used to calculate patients systolic, diastolic and mean arterial pressure. It is more accurate than commercially available automatic blood pressure cuff. Compared to an indwelling arterial catheter (an oldest direct method for blood pressure measurement), cuff method has a mean correlation of 0.70 - 0.80 whereas Vasotrac has a mean correlation of 0.90. The response time of Vasotrac is approximately 15 seconds. The wrist sensor fits adults of any size, can be used on either wrist, and is latex-free. Vasotrac can be used to monitor obese patients, patients with low cardiac output, hypothermia, or abnormal heart rhythm.

6PowerLab data acquisition system (34)

The PowerLab 4/30, Fig. 1.11, is a high-performance data acquisition system suitable for a wide range of research applications that require up to 4 input channels. It also offers analysis solutions for life science research and education applications.

Fig.1.11 PowerLab 4/30

The unit is capable of recording at speeds of up to 400 000 samples per second continuously to disk (aggregate), and is compatible with instruments, signal conditioners and transducers supplied by ADInstruments(e.g. MLT1010 Pulse Transducer), as well as many other brands. In addition to standard single-ended BNC inputs, the PowerLab 4/30 features 4 differential Pod ports that allow for direct connection of Pod signal conditioners and appropriate transducers.

Features:

- Four analog inputs: 4 single-ended (BNC) or 4 differential (Pod Port)
- Amplification range: ±2 mV to ±10 V full scale in 12 steps:
- Maximum input voltage: ±15 V
- Input impedance: ~ 1 MΩ || 100 pF
- Low-pass filters: 1 Hz – 1 kHz in 2:5:10 steps; 2 kHz, 25 kHz
- Input coupling: DC or 0.15 Hz (software-selectable)

- Frequency response (–3 dB): 25 kHz on 10 V range
- DC drift: Software corrected
- CMRR: 100 dB @ 100 Hz (differential mode, 100 mV – 2 mV Range)
- Input crosstalk: 75 dB minimum
- Two independent stimulator outputs
- External trigger input and signal triggering
- AC or DC coupling
- Digital inputs and outputs for external instrument control
- High-Speed USB 2.0 interface (supports USB 1.1) for connection toWindows
- Sampling
- ADC resolution: 16 bit (313 μV resolution on 10 V range)
- Maximum sampling rates: 200 kHz on one or two inputs

The systems are used with Windows or Macintosh computers to record and analyze physiological signals from human and animal subjects. In one compact unit, PowerLab systems perform the functions of chart recorders, XYT plotters, digital voltmeters and storage oscilloscopes.

Data Acquisition Hardware- PowerLab data acquisition units are smart peripheral devices that perform data acquisition, signal conditioning, and pre-processing.

- External signals are acquired through analog inputs and amplified before being digitized
- The signal is multiplexed to an analog-digital converter
- The digitized signal is transmitted to the computer using USB connection
- Software receives, displays, analyzes and records the data and analysis to the computer's hard disk

Typical applications include human and animal physiology, pharmacology, neurophysiology, biology, zoology, biochemistry, and biomedical engineering.

1.5: Aims and Objectives

It is understood that disease diagnosis by traditional pulse analysis (NadiPariksha) done on the radial artery, requires a long experience and a high level of skill. The interpretation is subjective, depending on the practitioner. Therefore it would be advisable to develop a data acquisition system which is objective and could be used in Indian Medical system for disease diagnosis. Attempt to make the pulse diagnosis system objective is the aim of the thesis.

As far as Indian scenario is concerned,Upadhayawasthe first one to report the use of Dudgeonsphygmograph for obtaining pulse tracings for Pulses and classified in accordance with *Nadi-Shashtra*. Scientists at BARC have recently developed an instruments based on Impedance plethysmographyfor measurement of blood flow. Output of this instrument is available in the form of pulses which are analyzed for the diagnosis purpose. This technique is invasive and it requires appropriate current to be flown through the body which is a matter of concern. Work on pulse analysis is in progress at Department of Computer Science and Engineering Indian Institute of Technology, (Mumbai). Researchers have developed a pulse-based diagnostic system, *NadiTarangini*using strain gauge beingresistive; strain gauge is sensitive to static pressure also which may mask the dynamic pulse signal. Mahesh et al from Indian Institute of Technology, Madras are developing a system for three pulse position using piezoelectric sensors for radial pulse. Present attempt is to add or substantiate in making the pulse diagnosis objective.

The *Ayurvedic* practitioner senses pulse using three fingers; *Vata, Pitta* and *kapha*positions; by applying pressure on radial artery of left (for female) or right (for male) hand. Main objective therefore is to convert arterial pressure into electrical signal by using pressure sensors. Different types of sensors e.g. resistive, capacitive, piezoelectric can be used for this purpose. But it is found that the signal obtained using piezoelectric transducer is more reliable and can be processed easily. The signal obtained from the sensor may have very small amplitude and may contain noise. The signal need to be processed and made clean for display and use. Developing a suitable signal conditioning circuit is the second objective of the work. Three sensors are required for collecting the data at three points on the radial artery. Three sensors of same characteristics are required and corresponding three signal conditioning should be identical. Developing such hardware is the next objective of the work. The pulse data at three points on the radial artery is to be digitized, collected, displayed, and stored for further analysis. This is planned to be done using LaB VIEW, a graphical programming language for engineering applications. Any new developed instrument needs validation. The same will be done by comparing the output of our system with the similar one commercially available.

Pulse data from a large number of subjects will be collected from single point; -Vata/Pitta/kapha and three points; Vata, Pitta and kapha; on the radial artery. The data is planned to be analysed in frequency and time domain. The results will be compared with the ones available in the literature.

We hope to show the feasibility of the developed system for classifying the obtained data in terms of Vata, Pitta and Kapha dominant Prakruti of the subjects.

Literature review indicates that researchers have developed the pulse detection system for single point and three point measurement. However these are not commercially available. Secondlycommercially available equipments are for some specific purpose and may not be very suitable for the research based on Ayurvedic medicine. The only commercial equipment, which may be suitable, is Power Lab data acquisition system. However,the sensors used along with the system are large in system and therefore not suitable for measurement at three pulse point simultaneously. Secondly, the instrument is very expensive. It is, therefore, necessary to develop our own equipment.

References

1) V. D. Lad,“Secrets of the Pulse: The ancient Art of Ayurvedic Pulse Diagnosis” 1st edition, Motilal Banarsidass(2005).
2) S. Upadhyaya, “NadiVijnaana”1stEdition, Vedic Life Sciences Pvt. Ltd.(1986).
3) G.K. & Pal, Pal, “PrivateTextbook of Practical Physiology” 2nd Edition Orient lackswan(2006).
4) L. Wang, L. S. Xu and K. Q. Wang, “Wrist pulse waveform variability analysis.” Proceedings of the World Engineers Convention (WEC2004). Shanghai, China November 2–6 (2004) 247.
5) K. Q. Wang, L. S.Xu, D. Zhang andC. Shi, “TCPD based pulse monitoring and analyzing.” Proceedings of the International Conference on Machine Learning and Cybernetics, 3 (2002) 1366.
6) C. T. Lee and L. Y. Wei,“Spectrum analysis of human pulse.” IEEE transactions on Biomedical Engineering, BME-30 (6), (1983) 348.
7) B.H. Wang and J.L. Xiang,“Detecting system and power spectral analysis of pulse signals of human body.” Proceedings of International conference on signal processing (1998) 1646.
8) Y. Z. Yoon, M. H. Lee and K. S.Soh,“Pulse type classification by varying contact pressure.” IEEE Engineering in Medicine and Biology (2000)106.
9) L. E. Chwang “Relationship between wrist-pulse characteristics and body conditions.”Proceedings of the Engineering Mechanics Conference. (2000).
10) J. Bhattacharya and P. P.Kanjilal. “Analysis and characterization of photo-plethysmographic signal.” IEEE transactions on biomedical engineering,48(2001) 5.
11) K. W. Mun and K. S. Soh, “Change of Arterial Pulse Shape during a Cold Pressure Test.” Journal of the Korean Physical Society, 40(2002) 289.
12) S. C. Millasseau, R. P. Kelly, J. M. Ritter and P. J. Chowienczyk, “Determination of age-related increases in large artery stiffness by digital pulse contour analysis.” Clinical Science,103 (2002) 371.
13) T. S. Manning, B. E. Shykoff and J. L. Izzo, “Validity and reliability of diastolic pulse contour analysis (Windkessel Model) in Humans.” Hypertension, 39 (2002) 963.

14) I. Hlimonenko, K. Meigas, R. Vahisalu, “Waveform analysis of peripheral pulse wave detected inthe fingertip with photoplethysmograph.” Meas. Sci. Rev.3 (2003) 49.

*15)*Wang. W. K., H.S.U. T-Lin, BAU J.G., WANG L.Y. “Evaluation of herbal formulas by pulse analysis method.” Acta Pharmacol. Sin.24 *(2003)* 145*.*

16) J McLaughlin, M McNeill, B Braun and P D McCormack. “Piezoelectric sensor determination of arterial pulse wave velocity.” Physiological Measurement 24 (2003) 693.

17) L. Wang, K. Q. Wang and L. S. Xu, “Recognizing wrist pulse waveforms with improved dynamic time warping algorithm.” Proceedings of the International Conference on Machine Learning and Cybernetics. Shanghai, China (2004) 3644.

18) Goor DA, Sheffy J, Schnall RP, Arditti A, Caspi A, Bragdon EE, ShepsDS. “Peripheral arterial tonometry: a diagnostic method for detection ofmyocardial ischemia induced during mental stress tests: a pilot study”.Clin Cardiol. 27(2004):137.

19)G. Bodlaj, J. Berg, G. Biesenbach and W. KlinWochenschr, “Diurnal variations of arterial stiffness and subendocardial perfusion: Noninvasively assessed using applanation tonometry in healthy young men”. The Middle European Journal of Medicine 117/9-10 (2005) 348.

20) L. Xu, M. Q. H. Meng, C. Shi, K. Wang, and N. Li, “Quantitative Analyses of Pulse Images in Traditional Chinese Medicine.” Medical acupuncture 20 (3) (2008) 175.

21) H. Wang, Y. Cheng. “A quantitative system for pulse diagnosis in Traditional Chinese Medicine”. Proceedings of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference Shanghai, China (2005).

22)S. Mahesh, M. Manivannan, T. Anandan, ”Three Radial Artery Pulse Sensor Design for Siddha Based Disease *Diagnosis” International Journal of Systemics, Cybernetics and Informatics (IJSCI)* (2008) 19.

23) Abhinav, Meghna Sareen, Mahendra Kumar, Sneh Anand, Ashok Salhan and Jayashree Santhosh, "NadiYantra : A robust system design to capture the signal From the radial artery for non-invasive diagnosis." 2nd International Conference on Bioinformatics and Biomedical Engineering (ICBBE) (2008) 1387.

24) A. Joshi, S. Chandran, V. K. Jayaraman and B. D. Kulkarni**.** **"***NadiTarangini***:** A pulse based diagnostic system". *29th Annual International Conference of the IEEE EMBS*, pages 2207-2210, (2007).

25) Joshi A. J. , Chandran S., Jayaraman V. K. and Kulkarni B. D., "Multifractality In Arterial Pulse" *19th International Conference on Pattern Recognition* (2008).

26) Joshi A. J. , Chandran S., Jayaraman V. K. and Kulkarni B. D., "Arterial pulse rate variability Analysis for Dignoses" *19th International Conference on Pattern Recognition* ICPR (2008).

27) Prasanna Kelkar , Sunil Karamchandani and Sameer K. JindalIdentifying Tridosha for Disease Characterisation in Morphology of an IPG Pulse Waveform"_*www.ayurlink.com*

28) S. Karamchandani, S. N. Merchant, U. B. Desai, G. D. Jindal. "Application of crisp and fuzzy clustering algorithms for identification of hidden patterns from plethysmographic observations on the Radial Pulse". *Conf. Proc. IEEE Eng. Med. Biol. Soc.,* pages 3978-81 (2010)

29) www.bloodpressurehistory.com for Dudgeon sphygmograph

30) www.colin-bp.co.jp

31) www.pulse-academy.eu/index.htm

32) www.pulsetrace.com

33) www.vasotrac.com

34) www.adinstruments.com

CHAPTER 2

DEVELOPMENT OF DATA ACQUISITION SYSTEM FOR RADIAL PULSE

2.0: Introduction:

Development of radial pulse data acquisition system, radial pulse data collection and data analysis are the main jobs to be carried out for fulfilling the aim of the thesis of converting the subjective method of pulse diagnosis (*Nadi Nidan*) into objective. In this chapter, the method of design and development of radial pulse data acquisition system is discussed. It involves selection of the sensor, development of signal conditioning circuit for single point measurement, development of signal conditioning circuits for three point measurements and validation of the data acquisition systems for single and three point systems.

Three different methods are used to make the pulse data acquisition system for single point measurement. They are as follows-

- Data acquisition system using Digital storage Oscilloscope (single point).
- Data acquisition system using NI PCI 6259 DAQ Card (single point).
- Data acquisition system using Microcontroller (89C51RD2) (single point).

Development of three point pulse Examination system using data acquisition card, NI USB6008 from National Instruments co., to make system portable is also reported. These are described in this chapter in details. Advantages and disadvantages of each of them are spelt out and compared. Reasons for selecting the appropriate ones for future work are also discussed.

2.1: Radial pulse and its characteristics:

Radial pulse is detected on radial artery by three fingers. The Radial pulse looked with Ayurvedic View and Modern View is described in articles 1.1 and 1.2 of Chapter1. The pulse rate varies from 60 to 100 per minute for healthy subject. Corresponding frequencies are 1 to 1.67 Hz. The pulse signal is susceptible to various noise sources. The two importance ones are (i) respiration frequency ranging between 0.2Hz to 0.3 Hz and (ii) ac mains frequency of 50 Hz.(1) These two noise signal need to be removed in order to obtain clean signal. An appropriate sensor needs to be selected for converting the pulse information in electrical form. Position of sensor on the wrist is adjusted to obtain appropriate signal amplitude. Details on selection of the sensors and the signal processing circuits are given in next articles.

2.2: Selection of Sensors:

Engineers have designed many kinds of pulse sensors (2) to acquire pulse waveforms, for example piezoelectric sensor, infrared sensor, PVDF sensor, acoustic sensor, liquid sensor, Doppler sensor, photoelectric sensor, laser and image sensor. Although the infrared sensor is more accurate, it can be influenced by the thickness of skin and vessel wall; PVDF sensor can be very small, but it is easily affected by temperature and easily interferes with each other. Acoustic sensor is easily influenced by the vibration of the body and the variation of environment. Liquid sensor can be greatly influenced by liquid. Doppler sensor has less accuracy. Photoelectric sensor can make the vessel inflate. Of all these kinds of pulse sensors, it is found that the pressure sensor may be the best one to imitate the physician's feeling of the pulse based on traditional pulse diagnosis

Pressure sensors can be piezoresistive type or piezoelectric type. Piezoresistive sensor detects passive as well as dynamic pressure and piezoelectric sensor detects the dynamic pulse pressure and rejects the static pressure operating on it, when pressed against the wrist. Since for radial pulse detection only dynamic pulse pressure is of interest, piezoelectric pulse sensor is selected. The transducer converts force applied to its active surface into an electrical signal. Position of sensor on the wrist is adjusted to obtain appropriate signal.

For Pulse detection, piezoelectric Pulse Transducer (MLT1010) from ADINSTRUMENTS (3) is selected for this work. It is shown in Fig.2.1
A typical output is 50-200 mV. Frequency response of this transducer is within 2.5 to 5000 Hz. Its Operating signal range is between 0 to 1 V for linear output range when applied across a 1 MΩ resistor. Typically 100 mV is the output for finger pulse .It varies from 20 mV to 500 mV depending on person. Its Weight is 25 g and Size (diameter x thickness) is 22 x 12 mm (0.87" x 0.47") having cable length of 1 m (3.3').

Fig.2.1: MLT 1010 Pulse transducer

The transducer is kept at radial artery using a Velcrow strip. Proper repositioning is required to obtain the best signal.

In *Ayurveda* the pulse is felt at three points on the radial artery (4) and consecutive points are finger tip (~ 10mm) away. The diameter of MLT 1010 Pulse transducer is 22 mm. Therefore it is not feasible to use three such MLT 1010 pulse transducers for detecting pulse at three points simultaneously. For simultaneous measurements at three points, ultrasonic sensors (See appendix A) Fig.2.2 (a) were used. The outer covering is removed and only piezo disk is used as a radial pulse sensor [Fig.2.2 (b)]. The diameter of piezo disc is 10 mm which is suitable for three point measurement. It operates on principle of piezoelectric effect.

Fig.2.2 (a) Encapsulated ultrasonic sensor

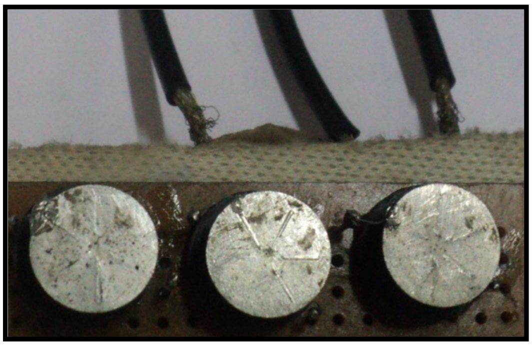


Fig.2.2 (b) Piezo disc

It was checked that the pulse output obtained by MLT 1010 Pulse transducer and selected ultrasonic sensors show similar pulse features.

The design and development of the signal processing circuit used to process the voltage output of these sensors is discussed in the next article.

2.3: Development of Signal Processing Circuit:

Block diagram of the signal processing circuit is shown in Fig.2.3. Pulse is detected using piezoelectric sensor. The signal processing circuit consists of buffer amplifier, high pass filter, signal amplifier, and active notch filter.

Circuit diagram is shown in Fig.2.3. Each block is described below.

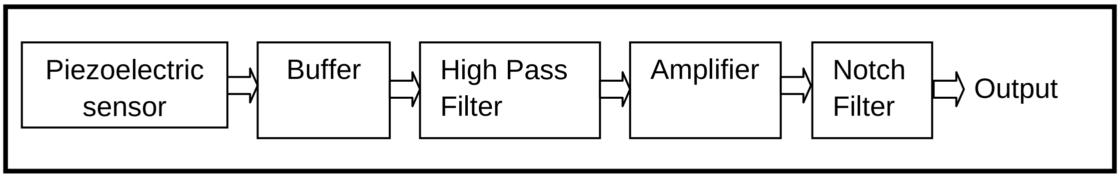


Fig. 2.3: Block diagram of Signal processing system.

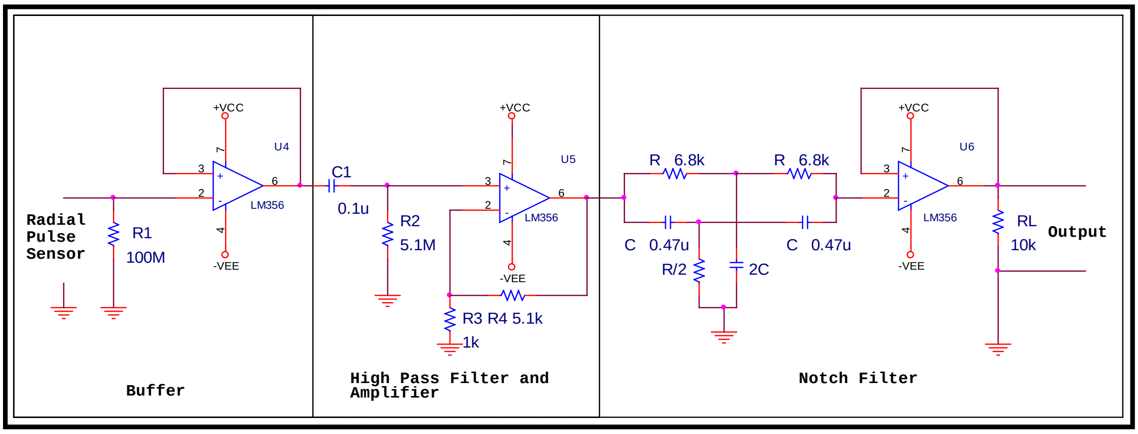


Fig. 2.4: Circuit diagram of Signal processing system.

2.3.1: Buffer:

Operating frequency range of MLT 1010 Pulse transducer is within 2.5 to 5000 Hz. Since the frequency of the radial pulse is about 1Hz, a 100MΩ resistance (R1) parallel to the sensor is connected in order to reduce the cut-off frequency to below 1 Hz. The electrical output of the transducer is connected to FET input opamp IC 356 operated in voltage mode since it has high input resistance (10^{12}Ω) (5). The output impedance is 40 Ω. It is used as a unity gain buffer amplifier which converts the high impedance of piezoelectric sensor into low impedance.

For three point pulse measurement ultrasonic sensors were used. The sensors have output capacitance of the order of 2400 pF at 1Khz. It represents very high impedance. The sensors were connected at the input of buffer amplifier mentioned above. The response of this buffer was almost same for the selected ultrasonic sensors. Therefore same signal processing circuit designed for MLT 1010 was used for these sensors also.

2.3.2: High Pass Filter and Amplifier:

A high pass filter is used to block respiration frequency. The respiration frequency lies in the range of 0.2 to 0.3 Hz. The High-pass filter is designed at the cut-off frequency of 0.3 Hz. The component values are calculated by using formula

$$f_c = \frac{1}{2\pi R_2 C_1}$$

The value of capacitor C_1 =0.1 µF is selected. The reactance of selected capacitor at 0.3 Hz is 5.3 MΩ. Therefore the value of resistor R_2 is selected as 5.3 MΩ. A nearest value of resistor used is 5.1 MΩ (Metal film type). At cutoff frequency the filter circuit works as a potential divider. At higher frequencies reactance of the capacitance is lower and therefore the output across the resistor will be larger than half the input voltage. At lower frequency voltage across the resistor will drop. The typical output of buffer is 100 mV. This voltage is in the operating range of the amplifier.

Secondly the input impedance of the Op Amp is 10^{12} Ω which is much larger than the resistor R2. Therefore the filter circuit will not get loaded. This justifies the choice of the values of components selected for the high pass filter. The simulation result of this filter using the designed components is shown in Fig. 2.5. The X axis represents Frequency in Hz and Y axis represents gain in db. The cutoff frequency from this response curve is 0.314Hz.

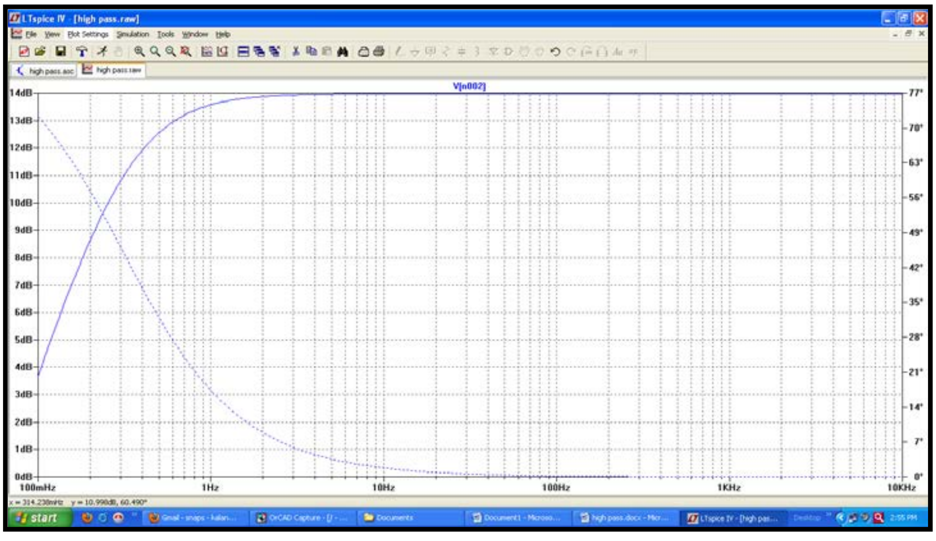


Fig. 2.5: Simulated response of RC high pass filter

The source of very low frequency of the order of fraction of Hertz is not available in the laboratory and therefore the practical response could not be taken.

The signal obtained from high pass filter is amplified using IC 356 amplifier in non-inverting mode. This gain is sufficient to give undistorted amplification in the range of input variation. For linear operation of an amplifier, the amplifier is designed for gain = 6.

2.3.3: Active Notch Filter:

AC mains frequency (In India it is 50Hz) is another source of noise in pulse signal. This enters when the sensor is placed on the wrist without proper insulation and /or if the circuit is not grounded. In order to remove this frequency a narrow band-suppress filter (Notch Filter) is used. The most commonly used notch filter is the Twin-T network [6]. This is a passive filter composed of two T is shaped networks (See Fig. 2.4). One T network is made of two resistors and a capacitor, while the other is made of two capacitors and a resistor.

The frequency at which attenuation occurs is called the notch frequency, and is given by,

$$f_N = \frac{1}{2\pi R\,C}$$

The passive twin –T network has a relatively low figure of merit Q. The Q of the network can be increased significantly if it is used with the voltage follower. To design an active notch filter for a specific notch out frequency f_N , The value of C is chosen such that C ≤ 1μF to get a specific notch frequency f_N and then the required value of R is calculated. The capacitor C = 0.47 μF and the Resistance values calculated from above formula comes out to be 6.777 KΩ. A nearest value of 6.8KΩ is used. The output and input impedances of this twin T filter are 13.6 KΩ. Increase in capacitance value (1.5 μF) will decrease the resistance value (2.1 KΩ) and therefore decrease in input and output impedances (9.2 KΩ). Similarly decrease in the capacitance value (0.1μF) will increase the resistance (31.8 KΩ) and therefore increase in the input and output impedances (63.6 KΩ).

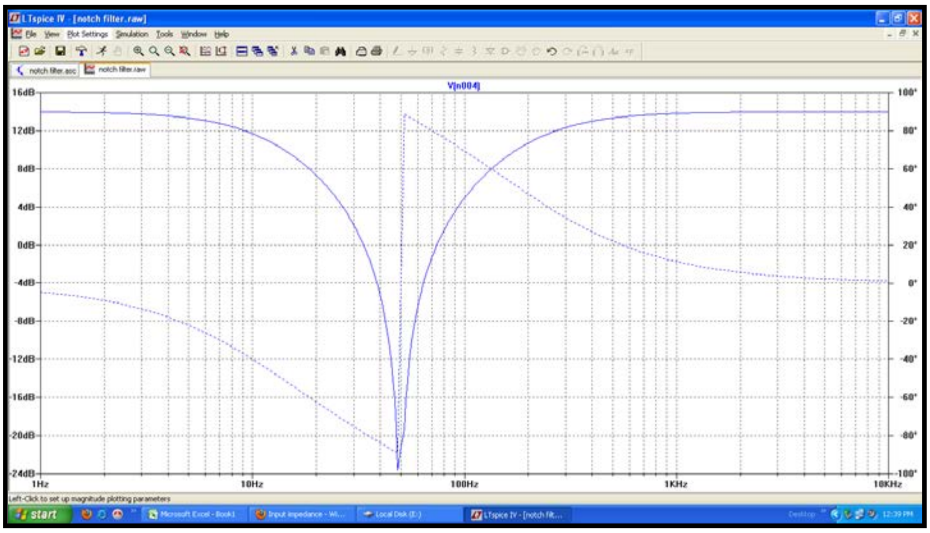


Fig.2.6(a) Simulation of response of Notch Filter

The values of resistance and capacitance values selected take care of the issues of input and output impedance matching. Metal film type resistance is selected for the experiments. Simulated response curve (Bode plot) with notch frequency of 50 Hz is given in Fig. 2.6(a).

The measured response curve of the notch filter designed and fabricated in the present work is shown in Fig. 2.6(b).The simulated response and the obtained response of are comparable. The simulated response shows that cutoff frequency is 56 Hz whereas the actual cutoff frequency is around 50 Hz.

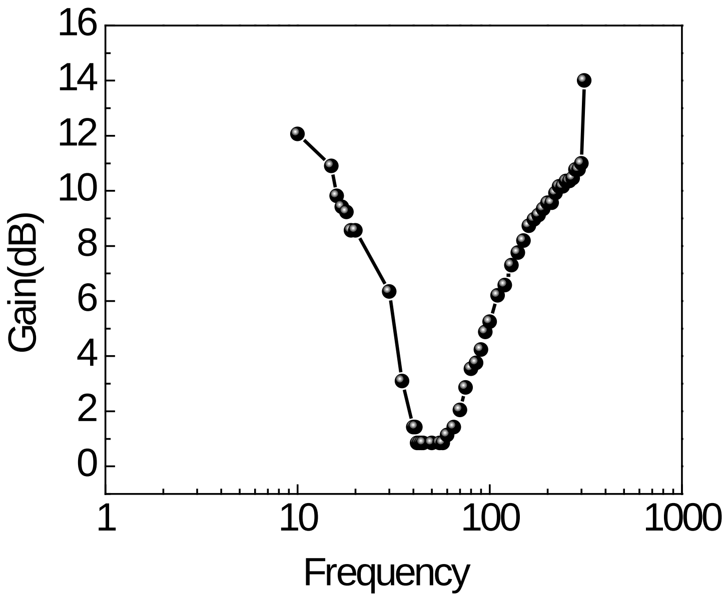


Fig.2.6 (b) Measured response of Notch Filter

2.3.4: Power Supply

A dual power supply of 12V/1A was designed to operate the data acquisition system. It consists of step down transformer, bridge rectifier, capacitor filter, 3 pin voltage regulators (IC7812&IC 7912).

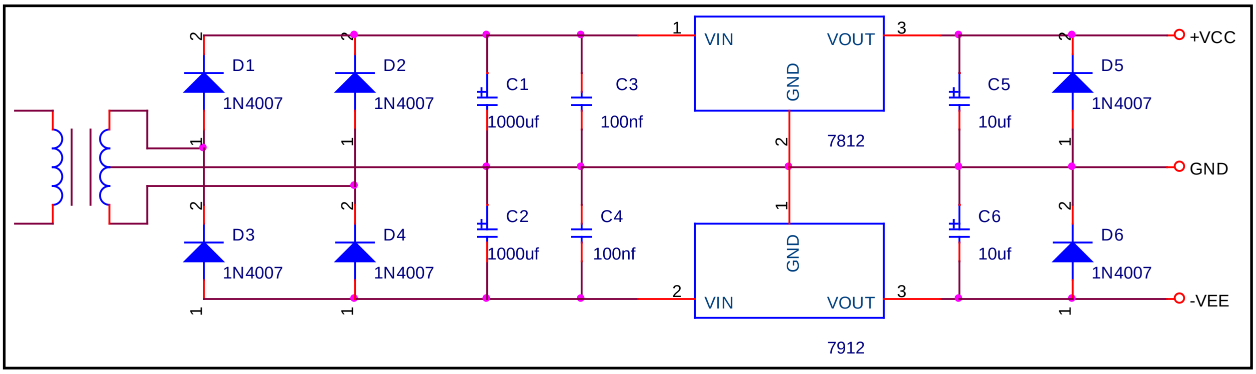


Fig.2.7: Circuit diagram of Dual power supply

The circuit was fabricated and tested for its performance. For portable system two 9V battery cells are used. It was observed that the noise contents in the data acquisition system are more when mains operated power supply is used. The noise content decrease when operated using battery cells.

2.4: Performance of the Signal Processing Circuit for Radial Pulse Detection:

To test the performance of the Signal Processing Circuit, the radial pulse waveforms of different subjects were recorded with digital storage oscilloscope (Model: DSO 3202A Agilent Technologies). Each subject was asked to relax and sit on the chair and rest his forearm on the laboratory table. Subject was further asked to keep the entire hand steady. Pulse Transducer MLT 1010 was placed on the position of artery at one of the pulse point. A small size sphygmomanometer cuff is wrapped around the wrist and was used to apply pressure on the transducer. The cuff was first inflated to a pressure at which the pulse wave starts to appear on the monitor screen. The pressure was applied to cuff just to get sufficient pulse amplitude. Position of sensor was adjusted on the wrist to get appropriate signal.

Fig.2.8 shows the typical recorded waveforms of subjects of different age groups. Upper curve in each screen shows pulse waveform and lower urve shows Fast Fourier Transform (FFT) of the same. The waveforms obtained from different subjects are different. The waveforms obtained are similar to the ones reported in the literature. It is observed from the waveforms obtained that in lower age range (22 year and 25 year), dichrotic notch is more prominent where as in higher age range (43 years and 60 years) it disappears. It is as expected as per the reports available in the literature. First peak in FFT gives frequency of pulse i.e. pulse rate. Further as seen from the lower FFT curves in each screen below, they range between 1 Hz and 1.41 Hz Above observations prove the successful development of signal processing circuit.

Digital Storage Oscilloscope has limited data storage capacity and limited Mathematical functions viz. Add, Subtract, Multiply and FFT. However large data is required to be collected for research on disease diagnosis.Further various statistical and analytical software's will be needed for analysis. It was therefore decided to develop a PC based system. Development of PC based system using Data acquisition card form National Instruments and Lab VIEW software is discussed in the next article.

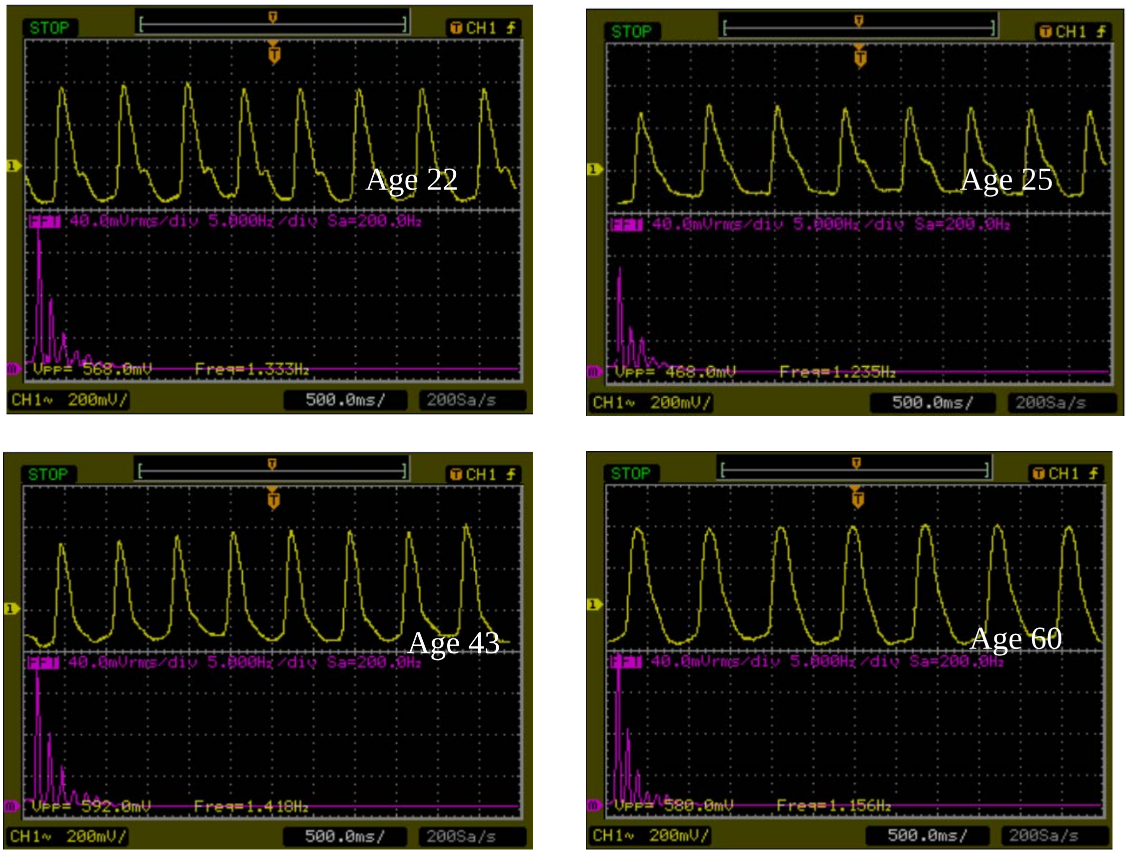


Fig. 2.8: Typical recorded waveforms of subjects of different age groups

2.5: Development Of PC Based Single Pulse Point Detection System:

Fig.2.9 shows block diagram of PC based Radial pulse data acquisition system. Selection and characteristics of piezoelectric transducer and development of signal processing circuit is explained in articles 2.3 and 2.4 above. To acquire data of large number of subjects, data acquisition card NI 6259 from National Instruments is selected. It is interfaced with PC using Lab VIEW (7). In this system the radial pulse signal is acquired and digitizes using DAQ card. Further the pulse waveform is displayed on PC screen and data is stored.

2.5.1: Data Acquisition Card: (National Instruments NI PCI -6259)

The DAQ hardware acts as the interface between the computer and the signal processing circuit. The National Instruments NI PCI-6259 PC Add on card [Fig.2.10] is a high-speed multifunction M Series data acquisition (DAQ) board optimized for superior accuracy at fast sampling rates.

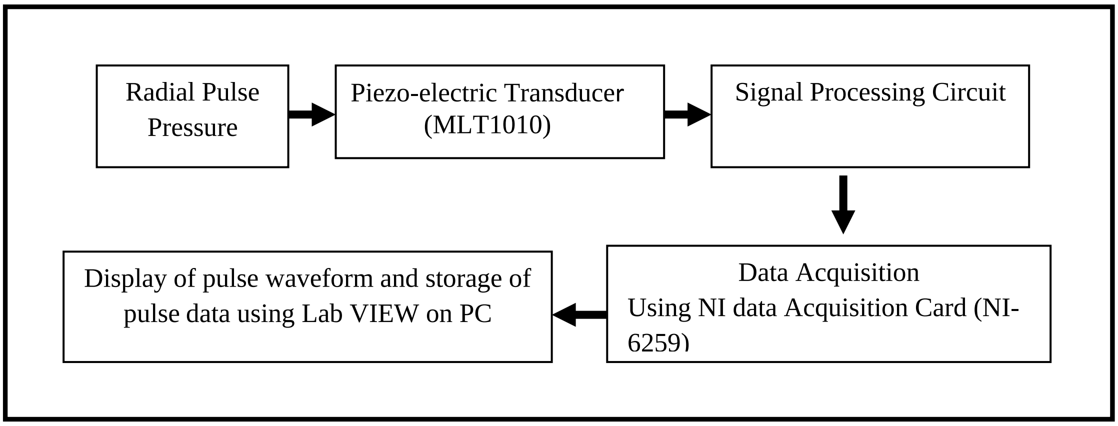


Fig.2.9: PC based Radial pulse data acquisition system using NI PCI 6259 DAQ Card

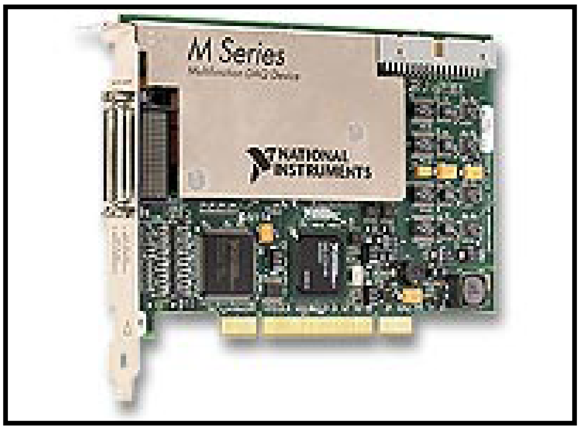


Fig.2.10 : DAQ Card-NI PCI 6259

NI PCI-6259 board has 16-bit analog-to-digital converter. It contains 32 analog input channels that can be configured to function in either a single-ended configuration or as 16 differential channels. A single-ended configuration was used and analog input channel 0 receives the radial pulse data. The sampling rate of 1.25 MS/s for each channel. (The data sheet is given in appendix). The DAQ board takes the analog input signal and sends it to the PC in digital form and the pulse waveform can be displayed on the computer using Lab VIEW software.

Lab VIEW is a graphical program development application, created by National Instrument in 1986 to integrate engineering task. Lab-VIEW programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes multiimeters and other measuring devices.

Lab VIEW contains a comprehensive set of tools for acquiring, analyzing, displaying and storing data, as well as tools to help you troubleshoot your code. In Lab-VIEW, a user interface known as front panel is created with controls and indicators. Controls are knobs, push buttons, dials, and other input devices. Indicators are graphs, LEDs, and other displays. After building the user interface, the code is added using VIs and structures to control the front panel objects. The block diagram contains this code.

The data is stored in the form of Lab VIEW measurement file (.lvm) format. LabVIEW measurement file (.lvm) is a text based file format for one dimensional data. This data can be used for offline analysis.

2.5.2: Radial Pulse Data Acquisition System:

Lab VIEW [7] programs are called virtual instruments (VIs) because they have the look and feel of physical system or instruments. VI has three main parts: the front panel, the block diagram, and the icon/connector. The front panel is the interactive user interface of a VI- a window through which the user interacts with the code.

The front panel is also used for viewing the program outputs. The front panel contains knobs, push buttons, graphs, and many other controls (similar to inputs) and indicators (similar to outputs).The block diagram is the source code for the VI. The source code is “written” in the G programming language.

The code is made up of graphical icons, wires. The block diagram is actually the executable code. Fig.2.11 (a) shows front panel of radial pulse data acquisition system. It shows recorded waveform of a subject. Pulse data is saved with *record data* knob. Stop knob is used to stop the recording of radial pulse. The block diagram of pulse detection system is shown in Fig.2.11 (b). The data is saved in Lab VIEW measurement file (.lvm) format for different subjects using developed system and was stored for future analysis.

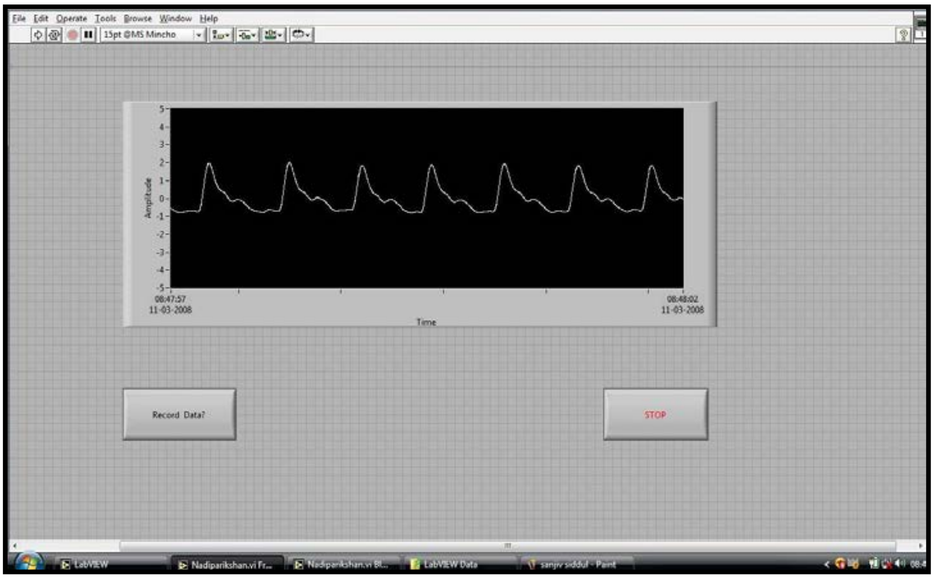


Fig.2.11 :(a) front panel of radial pulse acquisition system

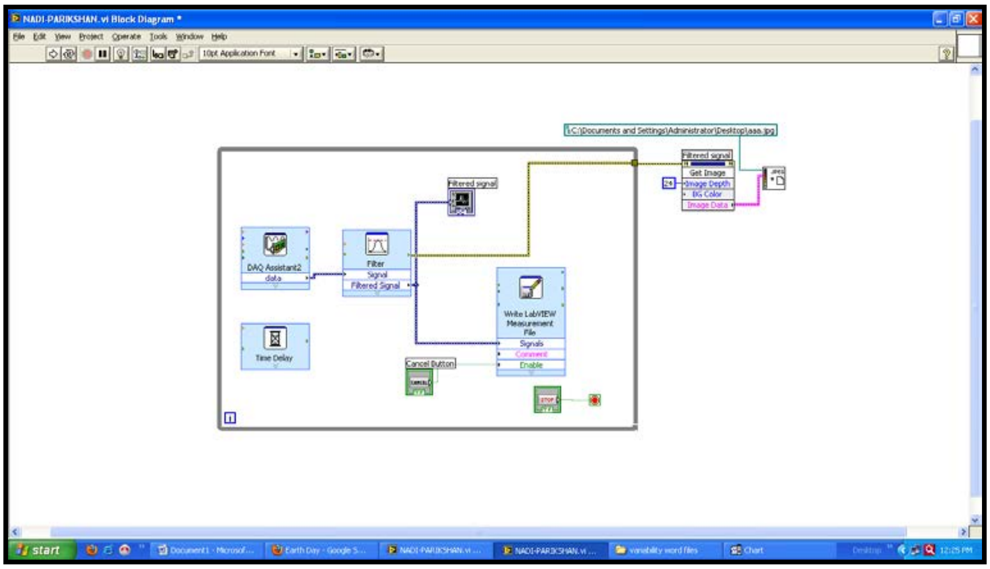


Fig.2.11 :(b) Block diagram of radial pulse acquisition system

The data was acquired at single point on radial artery. As can be seen from Fig. 2.11(a) the radial pulse shape acquired is similar to the one obtained using DSO. The advantage of this PC based system is that large number of radial pulse data can be stored and can be used for offline analysis purpose. The developed system is validated using commercially available system called Power lab 4/30 from AD Instruments. The results are explained in the next article.

2.5.3: Validation of Single Point Pulse Detection:

In order to validate the PC based single point radial pulse detection system developed in the present work the radial pulse data of 12 volunteers of normal health (subjects) was collected in the age group 22-34 years. The commercially available system called Power lab 4/30 from AD Instruments is used to validate our developed system.

The Power Lab 4/30 is a high-performance data acquisition system suitable for a wide range of research applications. It has 4 analog single ended (BNC) input channels. It has wide range of low-pass filters and also AC or DC coupling. The radial pulse data was collected using Power lab 4/30 and pulse examination system developed in the present work. Same pulse transducer (MLT1010) was used for collection of data from both the systems.

The same procedure for collecting the radial pulse data described in article 2.4 was used for collecting the data. Out of the 12 collected the radial pulse recorded of two subjects is shown in Fig.2.12. Fig.2.12 (a & b) represents the pulses recorded of subjects 1 and 2 by developed system and Fig.2.12 (c & d) represents the pulses recorded of same subjects using " Power Lab". The pulses recorded by developed system are in the integrated form [Fig.2.12 (a)] and the output pulses recorded by "Power Lab"[4] [See Fig 2.12 (c)] are in differentiated form. In order to get the pulse output in the same form the integrated pulse obtained from present system is differentiated [Fig.2.12(b)] and the differentiated pulse obtained from "Power Lab 4/30" is integrated [Fig. 2.12(d)]. Integrated shapes Fig 2.12(a) and Fig 2.12(d) are similar and differentiated pulses Fig. 2.12(b) and Fig. 2.12(c) are similar.

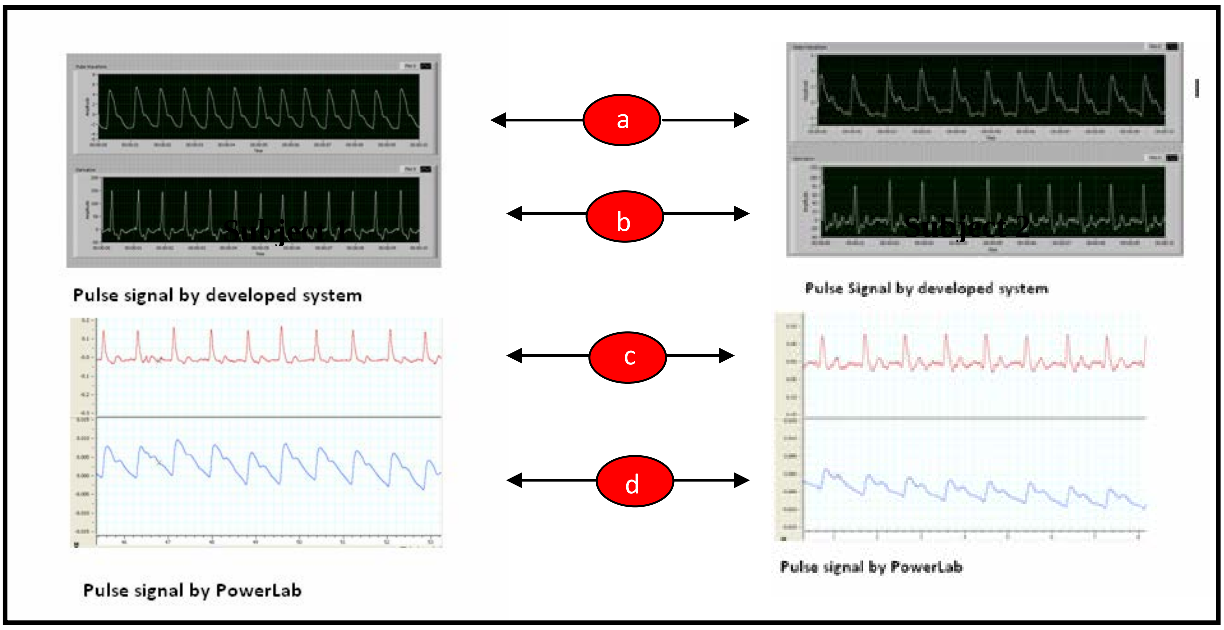


Fig. 2.12: Pulse signal obtained using single point pulse acquisition system and Pulse signal using power lab

a) Pulse signal *(Integrated form)* b) Pulse signal *(Diffentiated form)*
c) Pulse signal *(Diffentiated form)* d) Pulse signal *(Integrated form)*

In order to validate the system further the FFT analysis of the pulses obtained from both the systems is done. It is known that the frequency spectrum of the arterial systems has the majority of the power dispersed below 10 Hz [8]. In Fig.2.13 the Overlapped FFT waveform of one of the subject, obtained from both systems are shown. The main frequency harmonics of the arterial pulse, measured from both systems were located at 1 Hz, 2Hz, 3 Hz and 4 Hz. The pulses measured from the designed system did not contain any additional frequency components. It may be mentioned that data taken on remaining 10 subjects taken on both the systems when analyzed in the same way matches well.

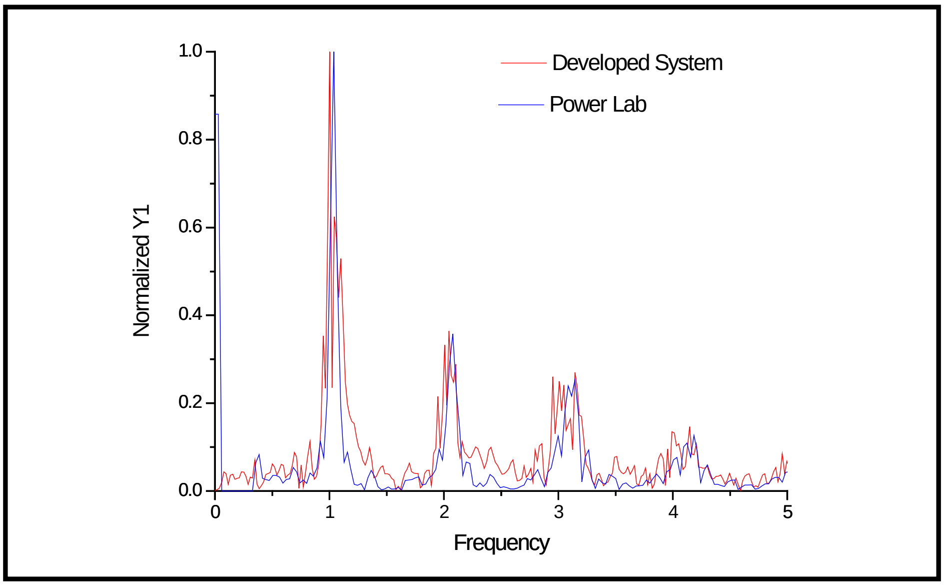


Fig 2.13: Overlapped FFT waveform obtained from "power Lab" and presently developed system

Above observations indicate that the performance of the developed single point radial pulse detection system is as good as the commercially available system.

2.6: Development of PC Based Three Point Pulse Detection and Analysis System:

It is known that *Nadi-Vaidya* carries out *Nadi-pariksha* using three fingers placed on radial artery. Therefore it is necessary to use three pressure sensors to measure the pressure at three points on radial artery to simulate the same. The piezoelectric transducer used for single pulse point has a diameter of 22 mm and therefore it is difficult to use this transducer for three pulse point measurement. This is because three pulse points – *Vata, Pitta* and *Kapha are* close to each other typically 10-12 mm away from each other therefore three piezoelectric based ultrasonic transducer from Prowave Electronic corp. were used as a pulse sensor. Photograph and the characteristics of single sensor are given in article 2.2.

For simultaneous measurement of the radial pulse at three points three ultrasonic sensors with the identical characteristics are mounted on acrylic module. Fig.2.14 (a) and (b) show the schematic diagram and finished sensor mount respectively. Sensor diameter is 10 mm and the distance between two sensors is kept approximately 6mm.

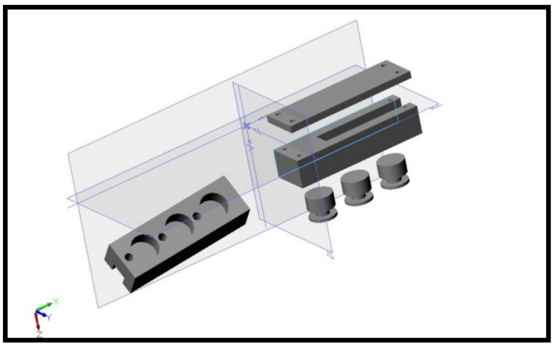


Fig 2.14 (a): Schematic of Sensor holding module

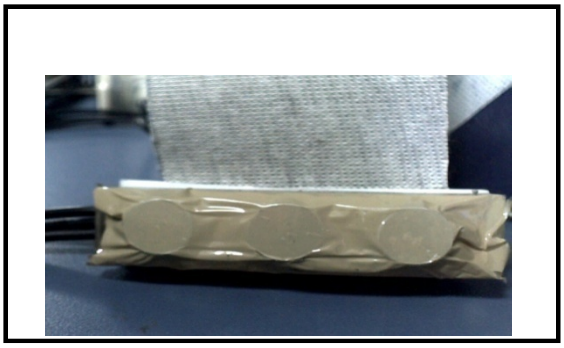


Fig 2.14 (b): Finished Sensor mount

This simulates the three fingers of *Nadi Vaidya*. Sensors are placed on wrist using Velcrow tape. The Three sensors shown above are further connected to three data acquisition units through coaxial cables.

Three identical data acquisition systems [Fig.2.15], similar to single point Fig. 2.4 (a) developed and tested for their performance. The performance of these acquisition systems was made identical (using NI PCI-6259 DAQ card).

The VI block diagram of the developed system is shown in Fig. 2.16 (a) and the front panel of three point examination system is shown in Fig. 2.16 (b). Fig.2.16 (b) includes the simultaneous recording of three pulses i.e. *Vata, Pitta and Kapha*.

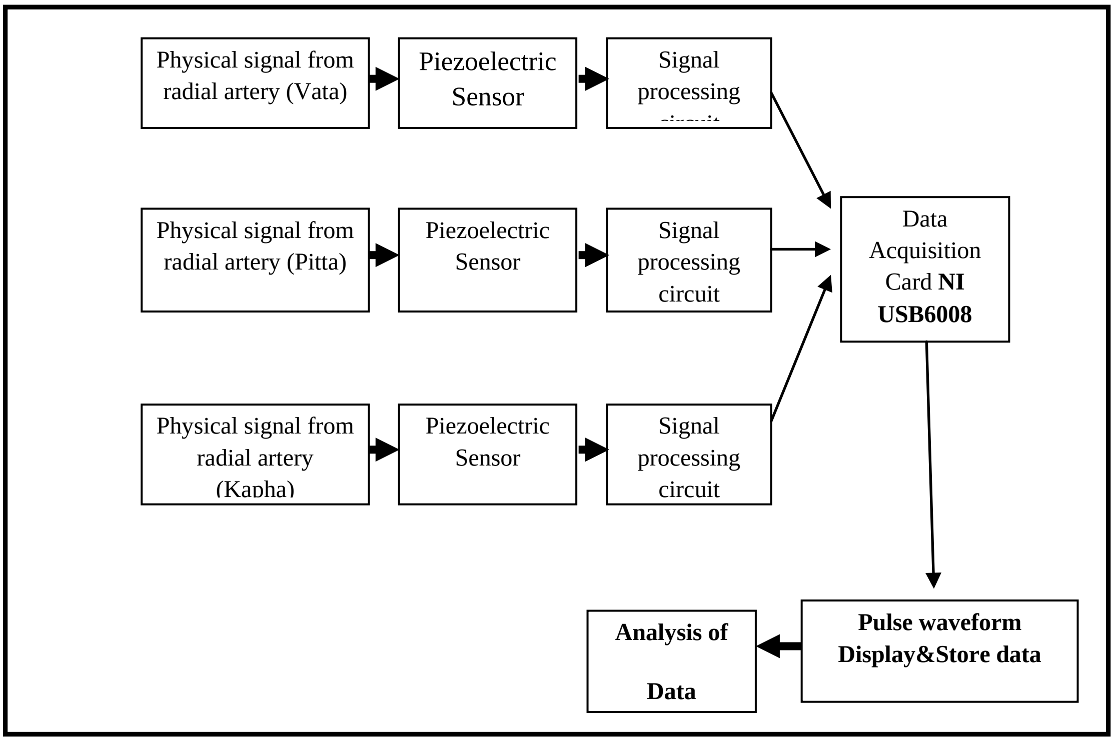


Fig.2.15: Block diagram of three point Pulse Examination system

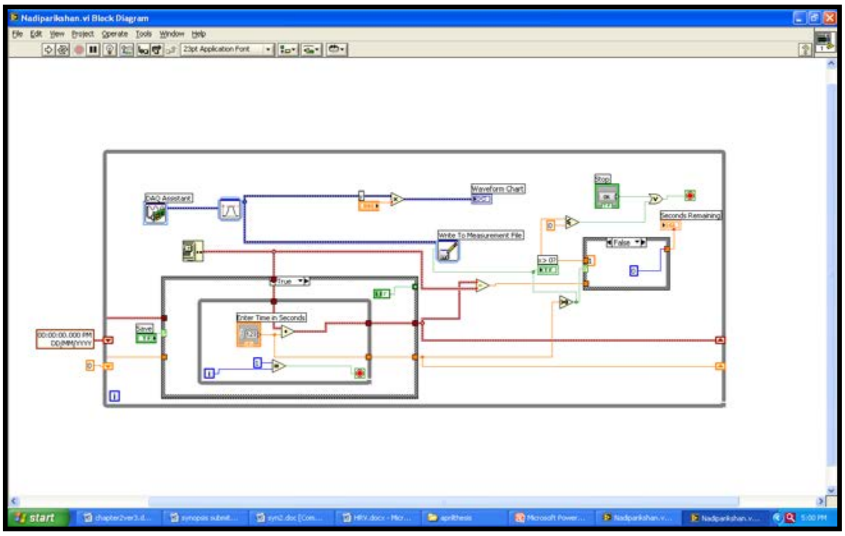


Fig. 2.16(a): VI block diagram of three point pulse Examination system

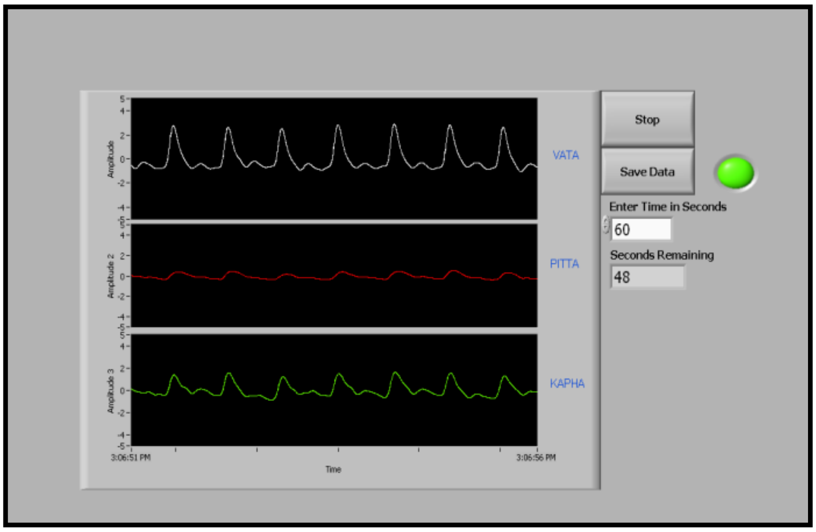


Fig. 2.16 (b): VI Front panel of three point Examination system

It was necessary to make the system portable for its outdoor use. For three point pulse examination system this is achieved by using the NI DAQ card NI 6008 and a laptop instead of using NI PCI-6259 DAQ card.

NI 6008 is USB based DAQ card which can be used to make system portable. NI6008 DAQ card has 12 bit resolution and maximum sampling rate of 10kS/s which is sufficient for radial pulse acquisition. This **PC based three point radial pulse Examination system** developed is named as **"*Nadi Parikshan Yantra*"** Fig.2.18 shows snapshot of *Nadi Parikshan Yantra.* Three channels are used to acquire three pulses of *vata, pitta* and *kapha.*

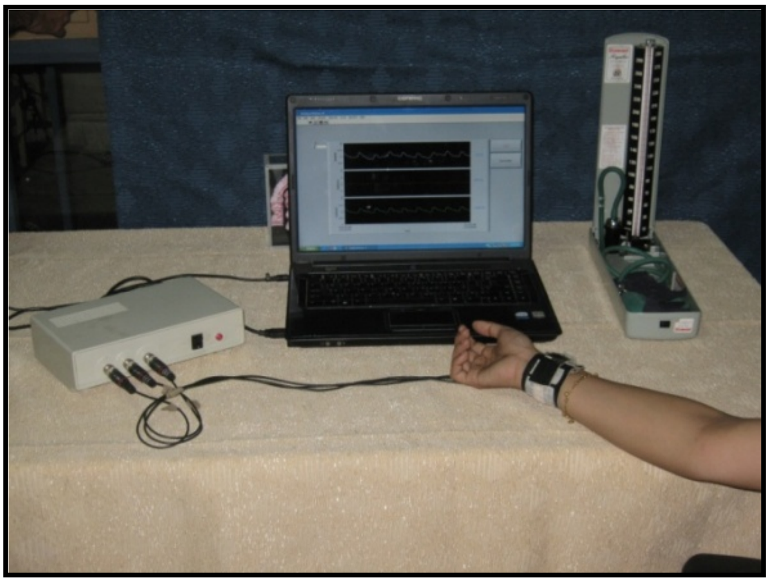


Fig. 2.17: Snap shot of "*Nadi Parikshan* Yantra"

2.7: Development of Microcontroller Based Data Acquisition System for Radial Pulse Detection:

Pulse detection system (*Nadi Parikshan Yantra)* using NI DAQ card NI 6259/ NI6008 DAQ card was explained in section 2.6. It is found that NI DAQ card has the large number of functions which are not required for the present application and is also expensive. Therefore a low cost microcontroller based data acquisition system (for single point) is developed. This is a handheld system and can be used to record pulse data at hospitals.

This section describes the development of microcontroller based data acquisition system for radial pulse detection. The system developed was used to detect, display and record the radial pulse signal for further analysis. The piezoelectric pulse sensor [MLT1010 by AD Instruments] was used to sense the radial pulse. Signal processing circuit described in section 2.3 was used to for preprocessing the pulse signal. A 12 bit ADC HI 574 [9] was used for digitization of pulse signal.

The microcontroller 89c51RD2 from Philips [10] was used to control ADC operation and serial communication with PC. VI (Lab VIEW program) was developed to acquire, display and record the arterial pulse signal. The signal was displayed on the Lab VIEW (Ver.8.2) front panel and recorded in text (.lmv) format for future use.

2.7.1: Data Acquisition using Microcontroller 89C51RD2

Data acquisition unit is designed to acquire and send the data to PC for further analysis. Fig 2.18 shows the block diagram of microcontroller data acquisition system. It is designed and built using ADC HI574A from Intersil and microcontroller 89C51RD2 from Philips. The ADC HI 574 A is 12 bit ADC with 40 kHz max sampling rate and is compatible to microprocessor interface. The input voltage range of the ADC is 0V to 10V. These specifications of the ADC are suitable for pulse signal which is within the range of 0V to 5V with maximum frequency of 25Hz.

The microcontroller, 89C51RD2 is 8 bit controller from 8051 family. It has an on chip flash program memory within the system programming and in application programming capability. ADC digitizes the signal into 12 bit data. This 12 bit data is further given to microcontroller. The IC MAX 232 converts the TTL signal protocol into RS-232 signal protocol. After getting data from ADC microcontroller communicates it with PC serially. Fig.2.19 gives the circuit diagram of data acquisition system. PCB was designed, fabricated and tested for its performance

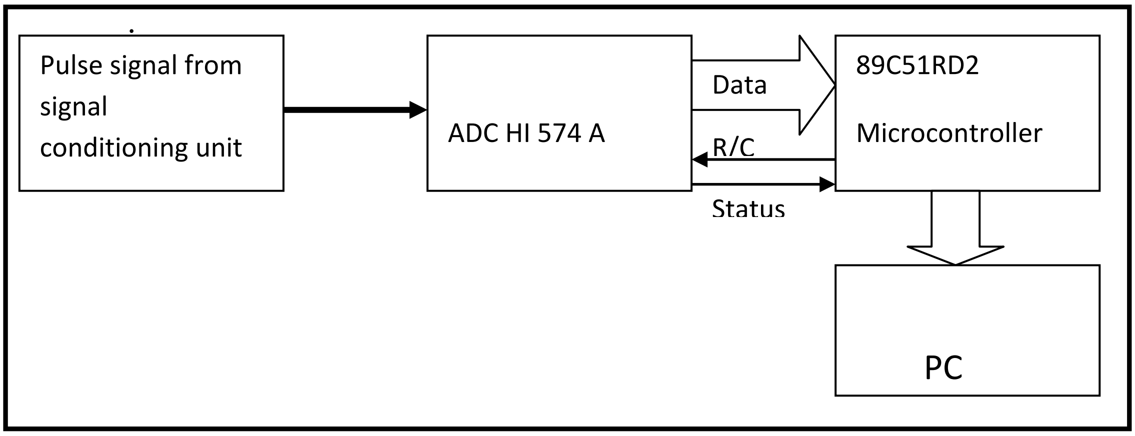


Fig. 2.18. Block diagram of the data acquisition unit

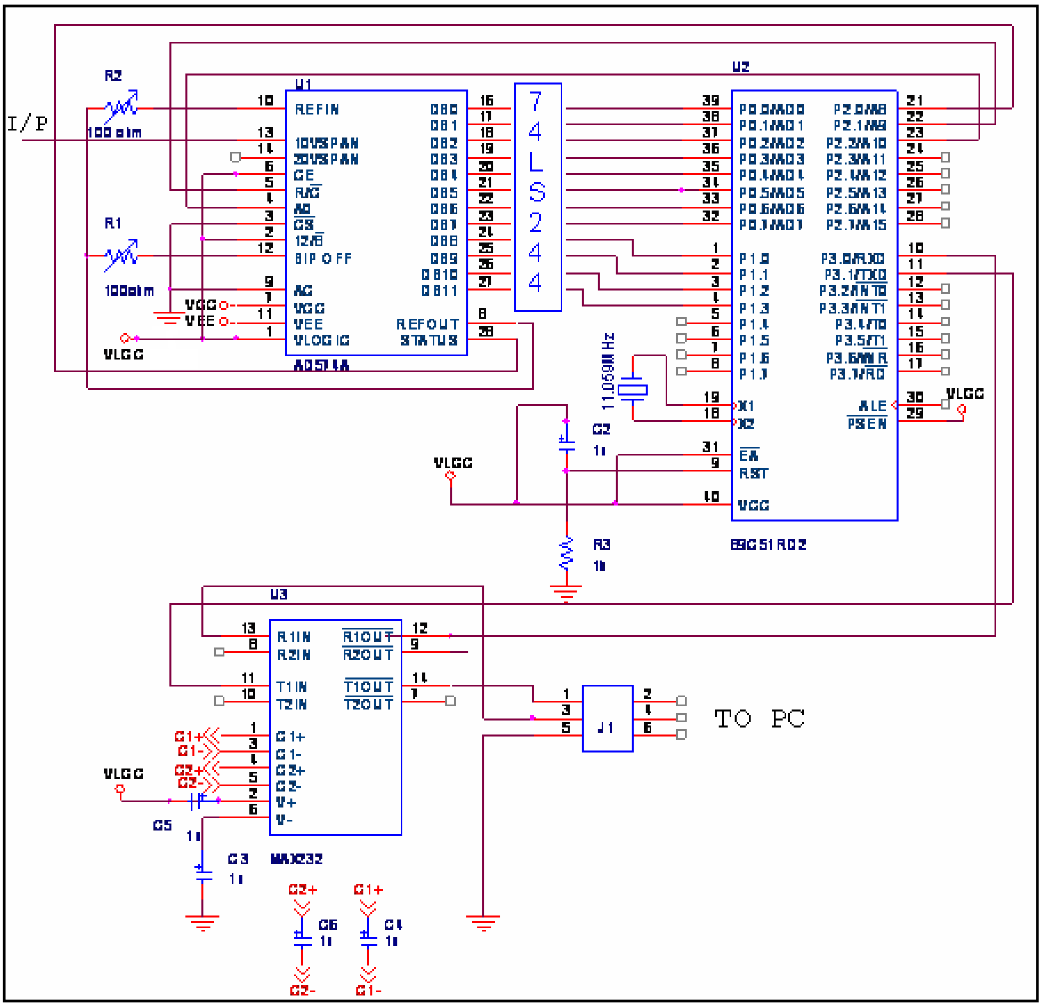


Fig. 2.19: Circuit diagram of microcontroller based data acquisition system

2.7.2: Software Programming

The software programs were developed for

a) Control of data acquisition system using microcontroller.

b) To display and record the pulse data using Lab VIEW.

a) To control the data acquisition and serial communication with PC the code is developed in Keil [11]. The flow chart is shown in Fig.2.20. The code includes digitization of analog pulse signal at a fixed sampling rate, convert it into RS 232 format and send it to PC.

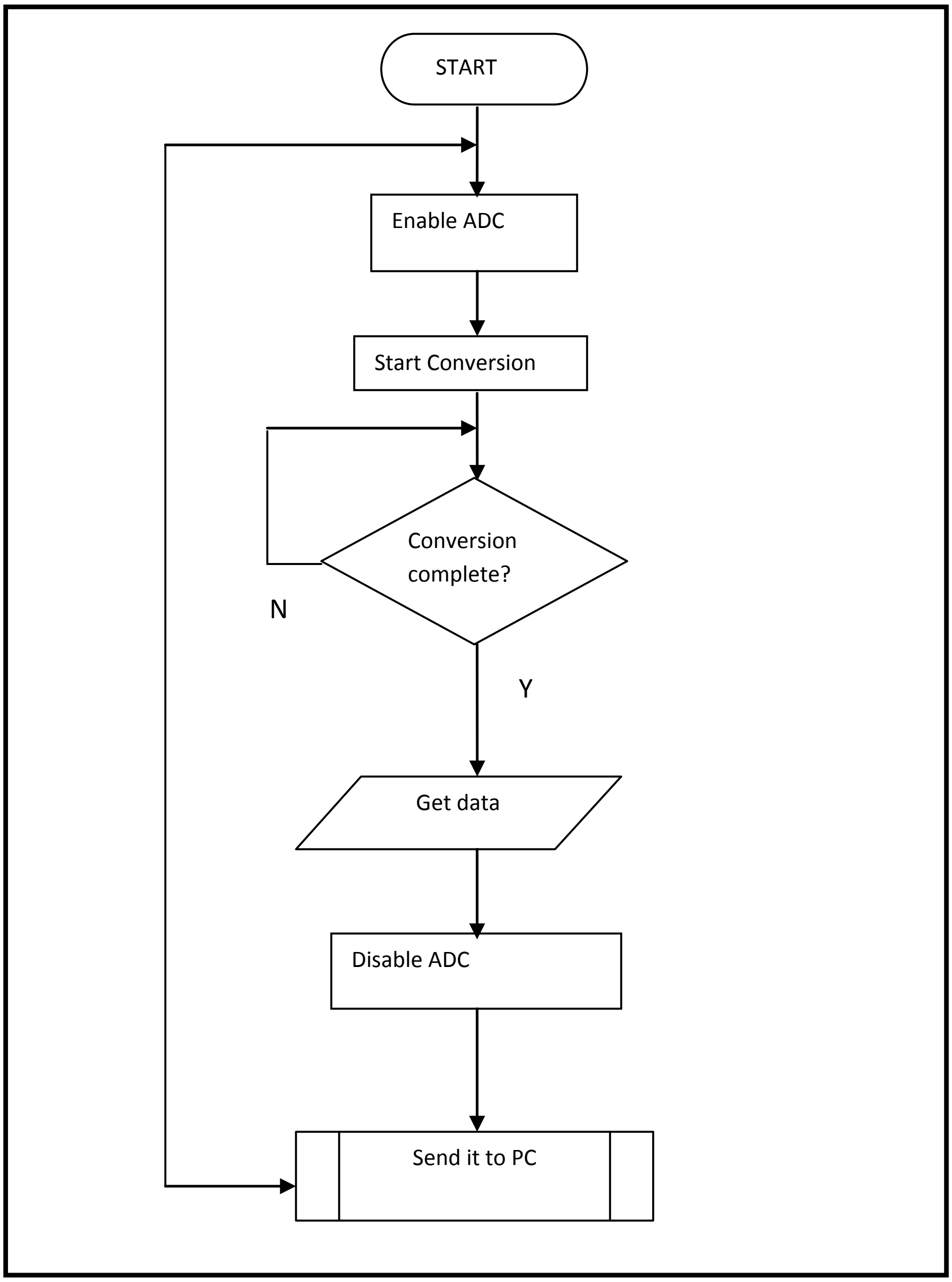


Fig.2.20: Flow chart of data acquisition and digitization

b) To acquire, display and record the pulse data in PC, Lab VIEW (Ver.8.2) was used which is explained in article 2.5. A Lab VIEW program called VI was developed to acquire, display and record the pulse. The main component in VI is VISA. VISA stands for Virtual Instrument Software Architecture. It is a single interface library for controlling GPIB, VXI, RS-232 and other types of instruments. Waveform chart is used to display the pulse signal. To record the pulse data a file I/O VI is included. The block diagram (Lab VIEW Code) is shown in Fig.2.21. Front panel i.e. user interface of the VI is shown in

Fig.2.22. User can set the serial communication parameters like baud rate; parity bit etc. To enable or disable the recording of waveform button control is provided. The path for file to be recorded is set in the block diagram. When new file is recorded, old one is replaced.

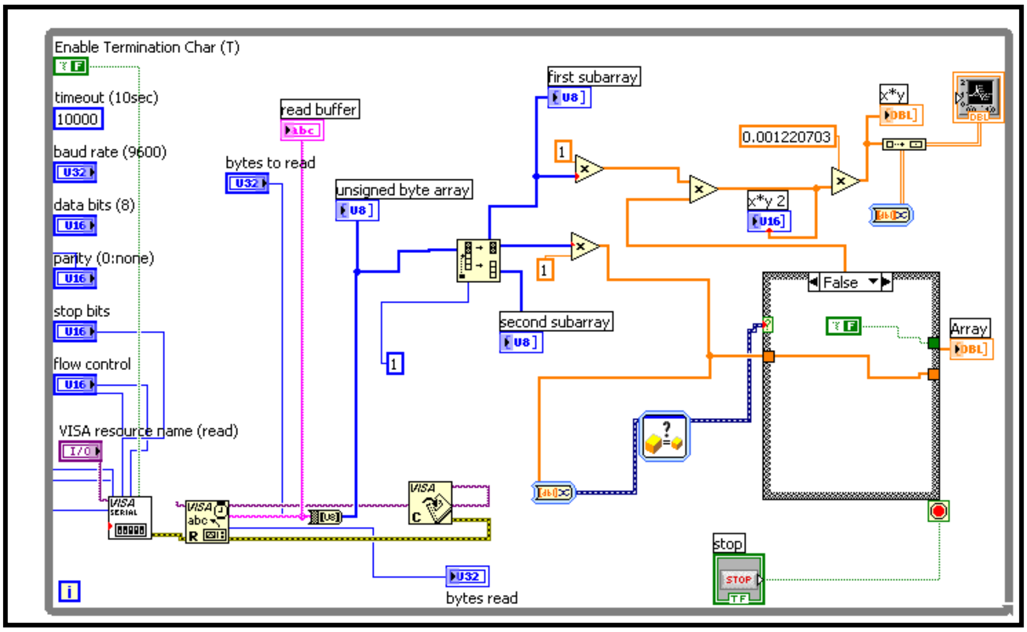


Fig.2.21. VI Block diagram of microcontroller based data acquisition system

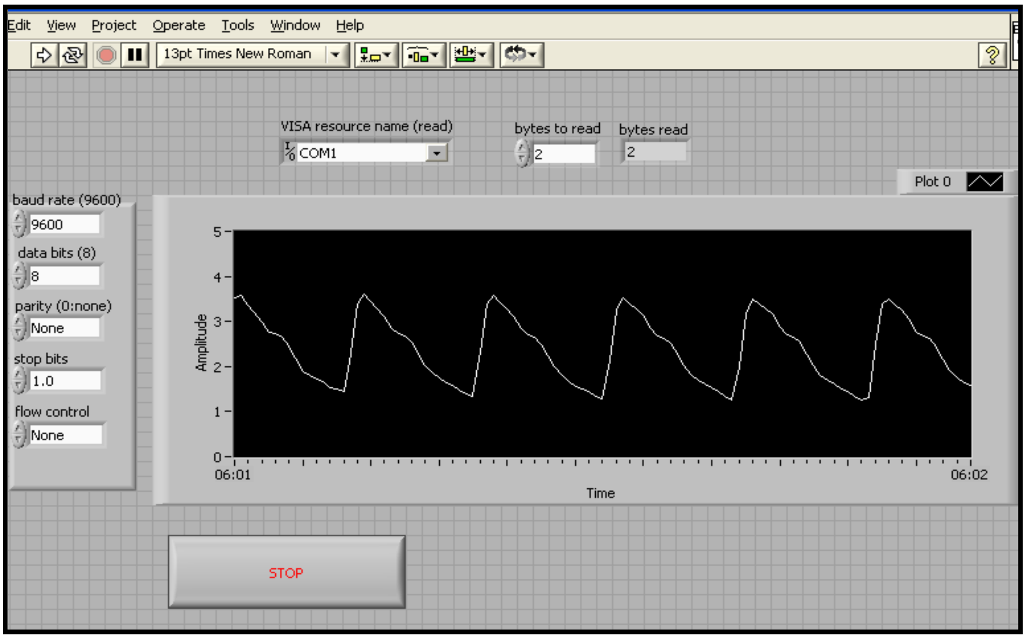
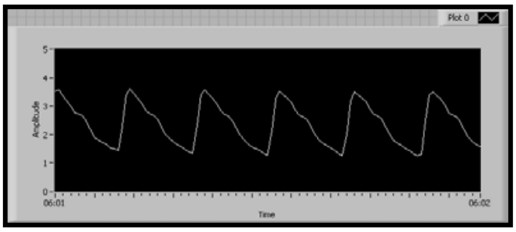


Fig.2.22. Front panel data acquisition unit

The measurements were performed on radial pulse of subjects with normal health of age between 23-25 years. Total 5 subjects were tested. The sensor is placed on wrist using Velcrow tape. The pulse signal is successfully acquired, displayed and recorded with the designed system.

The signal is simultaneously acquired by NI DAQ card 6259 using developed single point pulse acquisition system in this work [section 2.5]. The typical pulse waveforms acquired by microcontroller based system is shown in Fig.2.23 (a) and that by NI DAQ card is shown in Fig.2.23 (b).

Each file is saved in the text format for 1 min. Outputs by the both the systems regardless of minor noise in the output signal of the microcontroller based system are same. The noise can be removed in offline processing.



` **Fig. 2.23 (a).Pulse output of microcontroller based system**

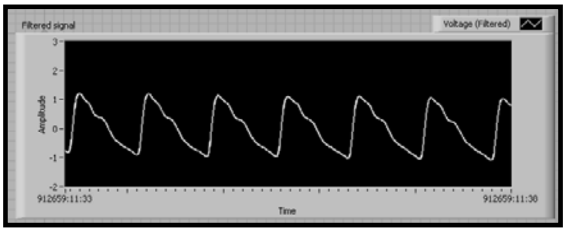


Fig. 2.23(b). Pulse output of system NI DAQ card 6259

The observations show that the microcontroller based single pulse data acquisition system is successfully developed.

2.8: Conclusions:

In an attempt to make the subjective method of radial pulse diagnosis into an objective method, this chapter reported the development of radial pulse data acquisition systems using Digital Storage Oscilloscope (single point). NI PCI 6259 DAQ Card (single point), NI USB 6008 (three point) DAQ card and Microcontroller (89C51RD2) (single point).

All the four systems are successfully developed and showed the feasibility of using them for radial pulse acquisition .The results obtained are as good as those of commercially available system (powerlab4/30).Out of these four, the three pulse point examination system-"*Nadi Parikshan Yantra*"-was used for pulse data collection and analysis.

References:

1. Hsieh C. W., Mao C. W., Young M.S., Yeh T. L. and Yeh S. J. "Respiratory effect on the pulse spectrum", Journal of medical Engineering & Technology, Volume 27, number 2 Page 77-84
2. Lisheng Xu, Max Q.-H. Meng, Cheng Shi, Kuanquan Wang, and Naimin Li, Quantitative Analyses of Pulse Images in Traditional Chinese Medicine Medical acupuncture Volume 20, (2008) Number 3.
3. www.adinstruments.com
4. Vasant D. Lad. "Secrets of the Pulse: The ancient Art of Ayurvedic Pulse Diagnosis", Motilal Banarsidass (2005).
5. www.national.com/ds/LF/LF/155.pdf- for OPAMP IC 356.
6. Ramakant Gayakwad "Op-Amps and linear integrated circuits", Fourth Ed.(2004).
7. Bishop R H "Learning Lab VIEW 7", Pearson Education, 1st Ed. (2005).
8. Wang B H, Xiang J L. "Detecting System and Power-Spectral Analysis of Pulse Signal of human Body", Proc of IEEE Inter Conf. on signal processing. Beijing.1646~1649, 1998.
9. Data sheet Analog devices 12 bit A/D converter AD574.
10. Philips data sheet – for Microcontroller 89C51 RD2.
11. www.keil.com

CHAPTER 3

DATA COLLECTION, RESULTS, ANALYSIS AND DISCUSSION

3.0 Introduction

After successful development of "*Nadi Parikshan Yantra*", it was used for collecting the radial pulse data of a large number of subjects. The same subjects were examined by Ayurvedic Physician (*Nadi Vaidya*) and the dominant *Dosha – Vata, Pitta or Kapha* – was identified. Correlation was established between the two with a view to use the electrical pulse data only for identifying the dominant *dosha* of the subject. The radial pulse data collected was analyzed in frequency and time domains.

The process of *data* collection, results obtained and analysis of pulse data are reported in this chapter. The data is collected from single dominant *dosha* point and all three *dosha* points. The results obtained are compared with the results available in the literature.

3.1 Data Collection

3.1.1: From *Nadi Vaidya*

The process of *Nadi Pariksha* by *Nadi Vaidya* involves placing the index, middle and ring fingers on the subject's forearm, a little below the wrist, on the radial artery [See Fig. 3.1] (1). They indicate the *Vata*, *Pitta* and *Kapha* *doshas* respectively.

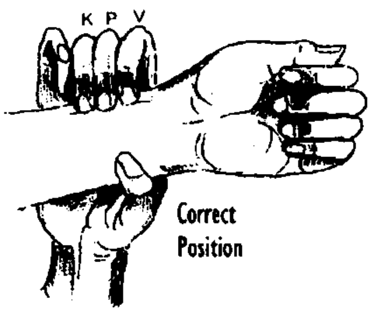


Fig. 3.1: Radial artery Positions indicating *Vata*, *Pitta* and *Kapha.*

Nadi-Vaidya examines the *Nadi* of a subject and determines whether subject's *prakruti* at that time is *Vata pradhan* (dominant), *Pitta pradhan* or *Kapha pradhan*. This information is noted down as a reference for further use. The position of the dominant *dosha* point is marked on the hand of the subject.

3.1.2 From Single Dominant *Dosha* Point On Radial Artery

The pressure sensor (MLT1010 Pulse transducer) having size 22 mm diameters was kept on the marked dominant *dosha* position and the electrical pulse obtained at the output of the "*Nadi Parikshan Yantra*" was recorded. It was then used for offline analysis.

3.1.3 From All Three *Dosha* Points On Radial Artery

Three sensor module [see Fig. 2.14(b)] developed using ultrasonic sensors is used for collecting the radial pulse data at three *dosha* points. The sensor module is pressed against the wrist with an optimum pressure. The electrical pulses obtained simultaneously at the three *dosha* positions using "*Nadi Parikshan Yantra*" were recorded and used for offline analysis.

3.1.4 Determining the Optimum Contact Pressure

It is to be noted that, *Nadi-Vaidya* applies some pressure on the wrist and at certain pressure he feels the pulse (Nadi). To determine the optimum contact pressure on the wrist, at which pulse waveform with minimum noise and maximum amplitude can be recorded, the pulse waveforms at different pressures starting from 20 mm of Hg, at which pulse starts appearing to 120 mm of Hg, at which pulse signal shows a significant decline, were taken. Pressure was varied by 20 mg and the applied pressure is read on sphygmomanometer. The optimum contact pressure should also be comfortable to the subject. Single sensor (MLT 1010) is used for these experiments.

Fig. 3.2 shows the pulse waveforms at different pressures applied on the radial artery. It is observed that as the contact pressure increases on the wrist, the amplitude of pulse first increases becomes maximum at certain pressure and then it decreases as the contact pressure increases. Average amplitude of waveform as a function of contact pressure is shown if Fig. 3.3.

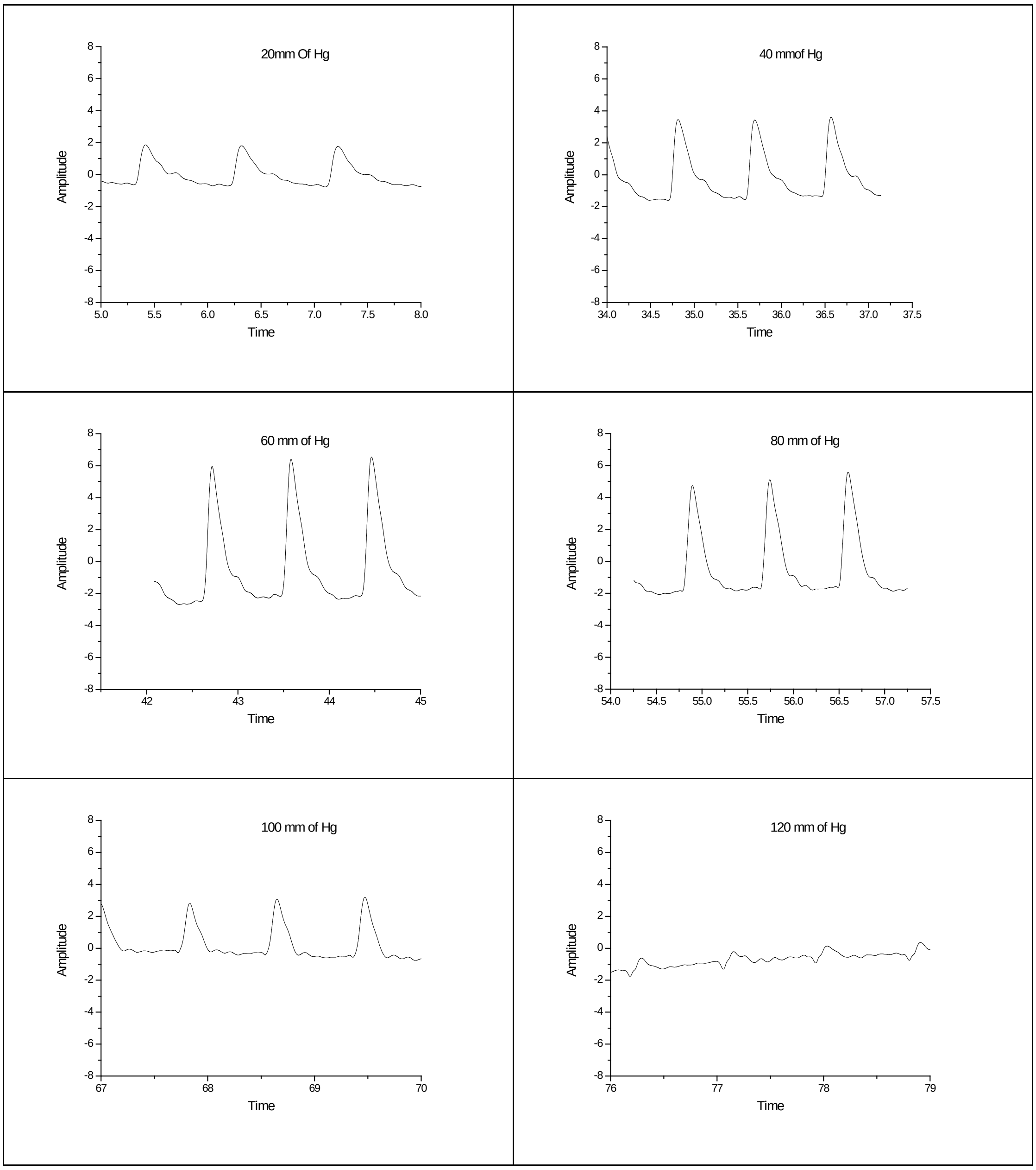


Fig. 3.2: Pulse waveforms for different pressures applied on the radial artery.

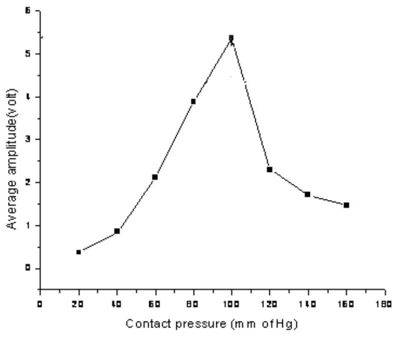


Fig. 3.3: Plot of average pulse amplitude against contact

Similar data for waveform amplitude as a function of contact pressure was collected for more number of subjects. Variation of the amplitude of pulse waveform with applied contact pressure for different subjects is shown in Fig 3.4.

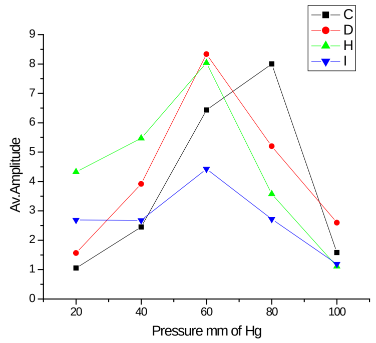


Fig. 3.4: Variation of the amplitude of pulse with applied contact pressure for different subjects.

It can be seen from the Fig. 3.4, that for different subjects, different contact pressure is required to get maximum pulse amplitude. Further it can be seen that this pressure lies between the 40 to 80 mm of Hg. The same range is used for further experiments. One gets clear shape of pulse in this range using selected sensor.

Yoon et al (2) have reported similar trend in their research paper. Actual values of the pressures used are found to be different. This may be because of the different way the pressure is applied on the artery.

3.1.5 Collection of Radial Pulse Waveforms

The subjects were invited to our laboratory for collection of data. Information regarding Name, Gender (Male/Female), Age, Height, Weight, Blood Pressure, Pulse rate of subjects was first collected. All measurements were performed in our laboratory. For radial pulse data collection each subject was asked to relax and sit on the chair after *Nadi-Vaidya's* examination and rest the forearm on the lab table. He was instructed to keep entire hand steady. Pressure between 40-80 mm of Hg was applied on the wrist of subjects. The subjects chosen were having normal health and no history of cardiovascular disease as per the information given by the subjects. Radial pulse data at single point marked by *Nadi-Vaidya* of 100 subjects was collected. The age group was between 22 to 78 years. In order to simulate the *Nadi Vaidya's* way of prediction *Radial* pulse data was also collected at three points (*Vata, Pitta and Kapha*) simultaneously on the wrist of additional 120 subjects using piezoelectric pressure sensors module [Fig.3.14 (b)]. The data with their relevant information was stored for further analysis.

3.2 Results on Single Point Radial Pulse Measurement

3.2.1 Pulse Waveform

As mentioned above data of total 100 subjects was collected. Out of these 59 were identified as *Vata* dominant, 33 were identified as *Pitta* dominant and 8 were identified as *Kapha dominant* by the *Nadi-Vaidya*.[See Fig.3.5] It may be mentioned that the '*Nadi-Vaidya'* who examined the subjects is expert in the field of *Nadi-Pariksha* and *Nadi-Pariksha* done by him is considered to be true. In the present work the electrical pulses obtained using pressure sensors are analyzed. The electrical pulse has following basic characteristics- amplitude, frequency, pulse rate, and shape of the pulse waveform. They can be analyzed in time and frequency domains.

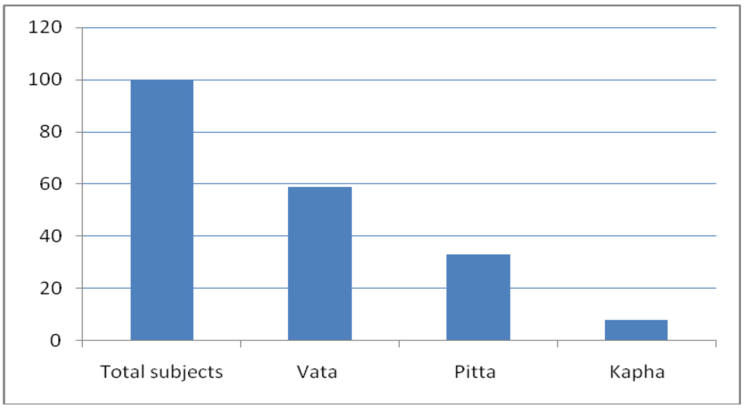
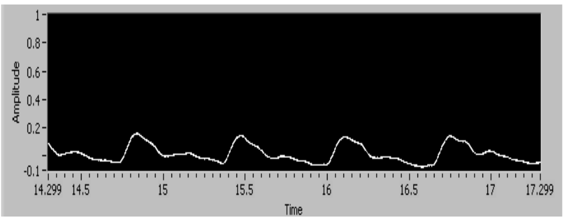
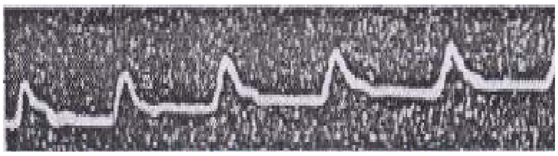


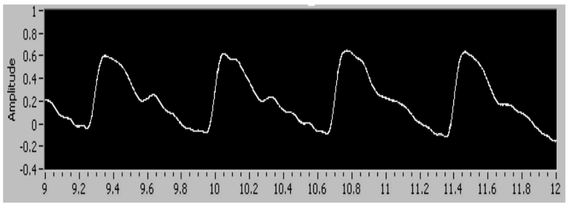
Fig. 3.5: Number of subjects

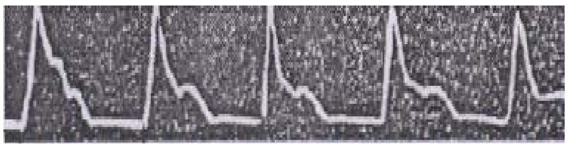
It is reported in the literature (3) that *Vata, Pitta and Kapha* pulse have different shapes as shown in Fig.3.6 (b) taken by Dudgeon's Sphygmograph. The shapes of the pulses obtained using piezoelectric pressure sensor from first few subjects in the present work and identified by *Nadi-Vaidya* as *Vata, Pitta* and *Kapha* are shown in Fig. 3.6(a). These are compared with the corresponding pulses in Fig.3.6 (b).



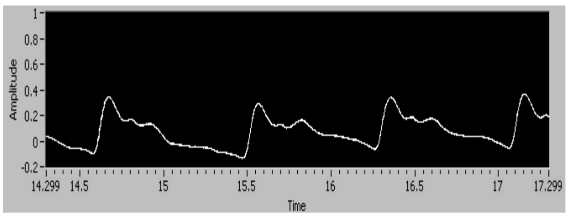


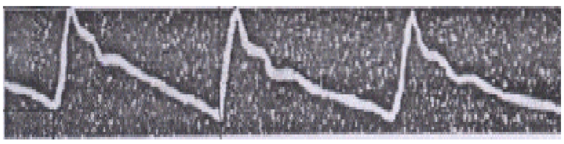
Typical *Vata* pulse





Typical *Pitta* pulse





Typical *Kapha* pulse

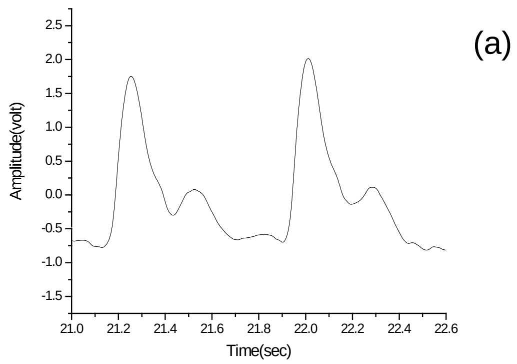
Fig. 3.6(a): *Vata, Pitta and Kapha* type pulses recorded using "Nadi Parikshan Yantra"

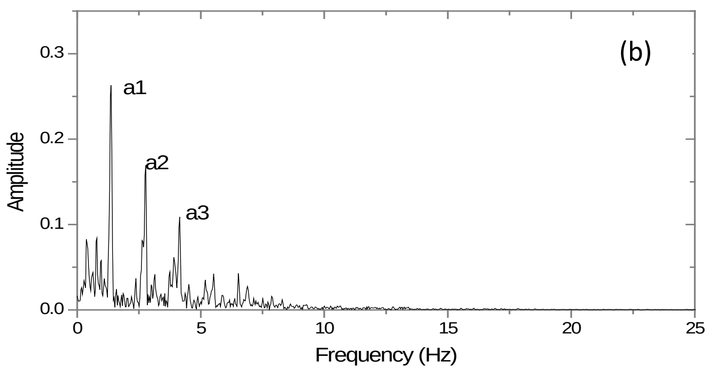
Fig. 3.6(b): *Vata, Pitta and Kapha* type pulses recorded using Dudgeon's Sphygmograph (3).

Comparison indicates that the shapes are similar. However as the data size increased the mismatch also increased indicating that shape only is not sufficient to classify the pulse type. Further it is possible that a subject may have two or more dominant *dosha.*

3.2.2 Frequency Domain Analysis of Radial Pulse Waveform

Frequency analysis is a powerful tool to analyze pulse waveform (4). Radial pulse waveform is a low frequency physiological signal. The variation in frequency over the duration of a signal is of great interest when trying to understand the physiological system. It is reported that the bandwidth of radial pulse is dc to 40 Hz (5). Therefore the sampling rate of 1000 Hz used in the developed system is enough to capture all the frequency components present in pulse spectrum. Fig.3.7 (a) is a typical pulse waveform. Fig.3.7 (b) is its FFT and Fig.3.7(c) shows power spectrum of the pulse.





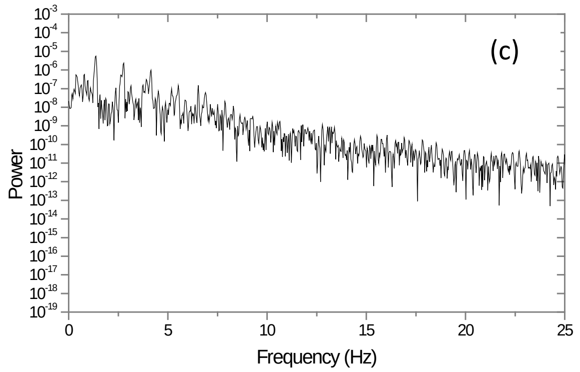


Fig 3.7 (a): Typical Radial Pulse (b) Magnitude spectra FFT (c) power spectrum.

From Fig. 3.7(b), it is observed that there are three distinct and prominent harmonic frequencies present in the waveforms. These frequencies are 1.36 Hz, 2.750 Hz, & 4.078 Hz. The highest peak, at 1.36 Hz in Fig 3.7 (b), is the fundamental frequency corresponds to the *pulse rate* of the subject. Power spectrum is a plot of power Vs frequency which gives the harmonic power in a signal. It is reported that the spectral energy of the pulse signal nearly distributes within 10 Hz (5). The same is observed in the present work.

3.2.2.1 Pulse Rate Analysis

The pulse data collected of 100 subjects using single point measurement is considered for analysis. As diagnosed by *Nadi Vaidya,* out of total number 100, 59 are of *Vata* dominant, 33 are of *Pitta* dominant and 8 are of *Kapha* dominant.

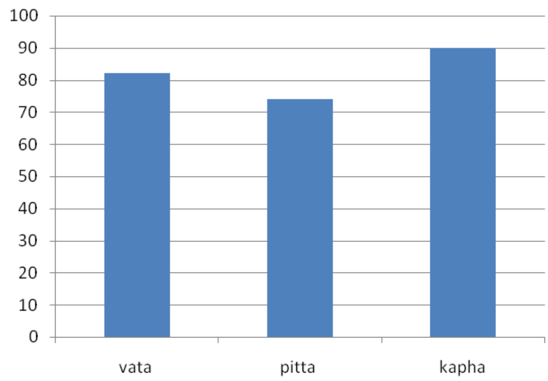


Fig. 3.8: Mean pulse rate of *Vata, Pitta* and *Kapha* dominant subjects.

Pulse rate was calculated by taking the FFT of recorded pulse. As mentioned above the first frequency component gives the pulse rate. Mean pulse rate for *Vata, Pitta* and *Kapha* type pulses was calculated and bar graph is shown in Fig.3.8. It is observed that *Kapha* dominant pulses are having higher pulse rate, *Vata* dominant pulses have moderate pulse rate and *Pitta* type have lower pulse rate. It is reported (3) that pulse rate is maximum for *Vata* pulse (80 to 95), minimum for *Kapha* (50 to 60) and moderate value for *Pitta* (70 to 80). The result obtained for *Kapha* was not in agreement with the literature whereas *Vata* and *Pitta* shows similar trend. This may be due to the fact that the *Nadi-Vaidya* was asked to identify only the dominant *dosha*. However it is possible that other *dosha* may have influence on pulse rate and therefore it is not advisable to analyze the data only on the basis of the pulse rate.

Further the data is also statistically analyzed. Mean pulse rate of *Vata* dominant pulse was 80±12, of *Pitta* pulse is77±8.6 and that of *Kapha* pulse is 90±12. Statistical comparison between *Vata* and *Pitta* group shows that there is no significant difference between *Vata* and *Pitta* pulse rates at the 0.05 level. Statistical comparison between *Pitta* and *Kapha* shows that there is a significant difference between *Pitta* and *Kapha* pulse rates at the 0.05 level and statistical comparison between *Vata* and *Kapha* shows that there is a significant difference between *Vata* and *Kapha* pulses at the 0.05 level. It indicates that large data need to be collected before making any conclusive remarks.

3.2.2.2 Radial Pulse Rate Variability Analysis

Radial Pulse rate contains nonlinear properties because of the complex regulation mechanism controlling it (6). Joshi et al used nonlinear method of Poincare plot to study the radial pulse variability. Poincare plot is a graphical representation of the correlation between consecutive radial (arterial) pulse interval (API). Fig. 3.9 (a) shows typical healthy API time series and its Poincare plot whereas Fig. 3.9 (b) shows irregular radial pulse API time series and Poincare plot.

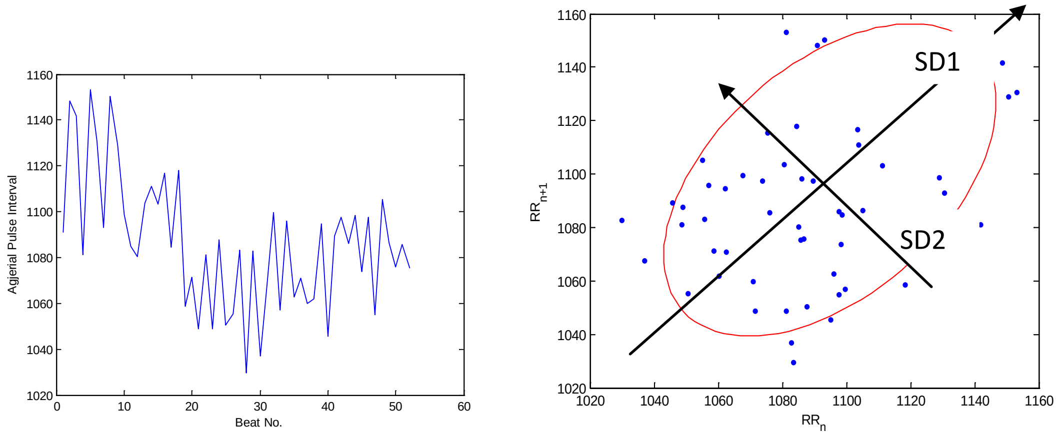


Fig 3.9 (a): A typical healthy radial pulse API signal and Poincare plot.

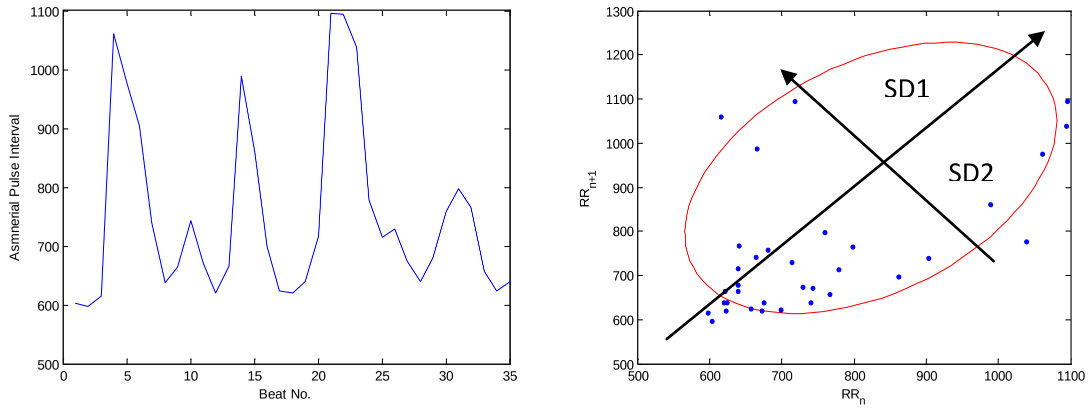
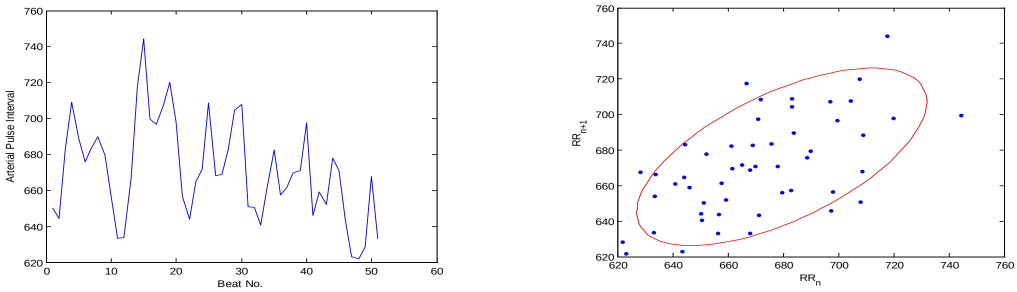


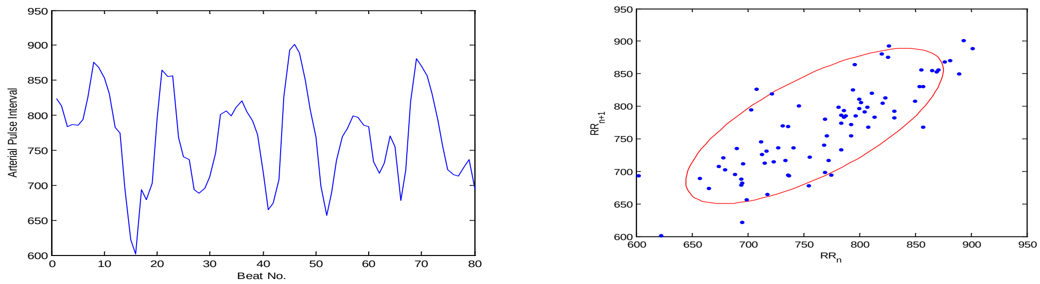
Fig 3.9(b): A irregular radial pulse API signal and Poincare plot.

In the Poincare plot SD1 and SD2 are the dispersions of points perpendicular and along the axis of line of identity. The points towards the top in the Poincare plot indicate two consecutive increasing intervals (i.e. pulse rate is decreasing), while the bottom left points indicate two consecutive decreasing intervals (i.e. pulse rate is increasing). This is described by fitting ellipse on the line of identity at 45° to the normal axis. Thus SD1 and SD2 are the length of the two axes of the ellipse. SD1 indicates short term variability and SD2 indicates long term variability. Poincare plot of a subject having irregular pulse rate [Fig. 3.9 (b)] shows a different coverage of points.

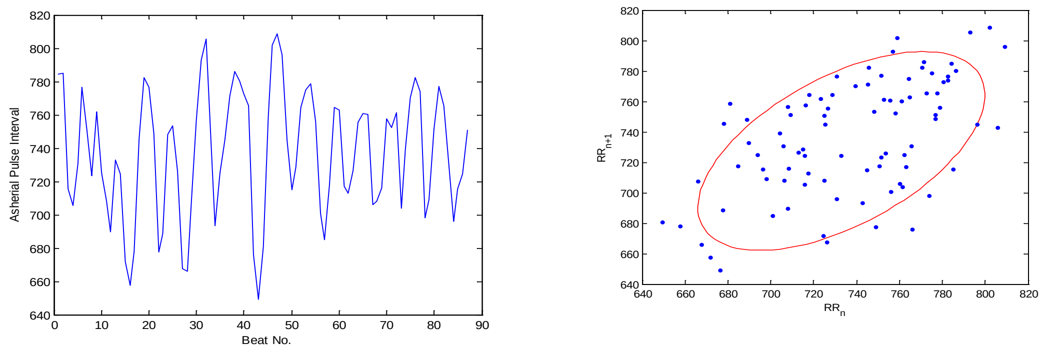
API time series and its Poincare plots of the results obtained in the present work are shown in following figures. Fig. 3.10(a-c) show the API and Poincare plots of *vata* type identified subjects, Fig. 3.11(a-c) show the API and Poincare plots of *pitta* type identified subjects and Fig. 3.12(a-c) show the API and Poincare plots of *kapha* type identified subjects. In each case data from three subjects is presented.



(a)Subject1

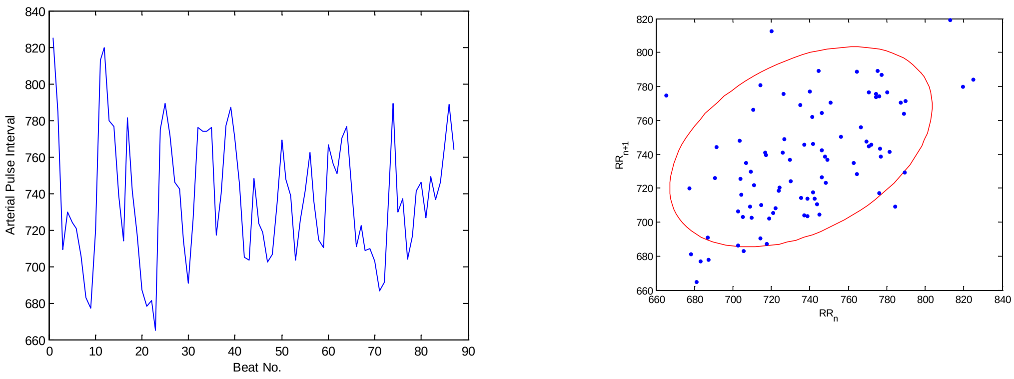


(b) Subject 2

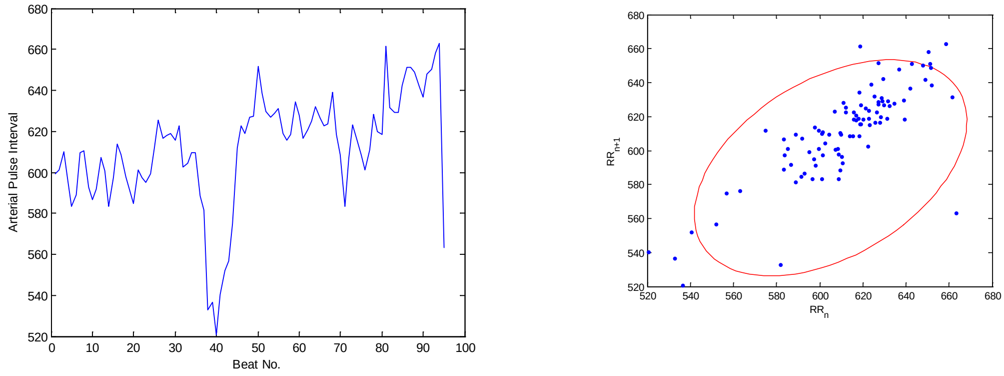


(c)Subject3

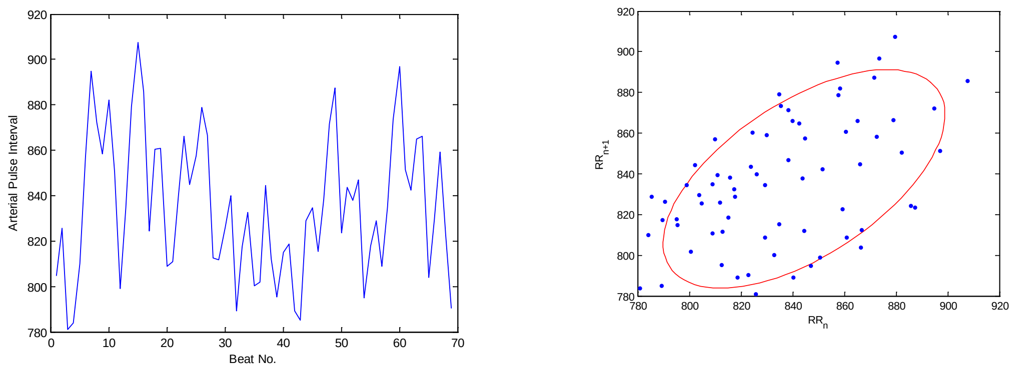
Fig. 3.10: API signal and Poincare plot for *Vata* type pulses



(a)Subject1

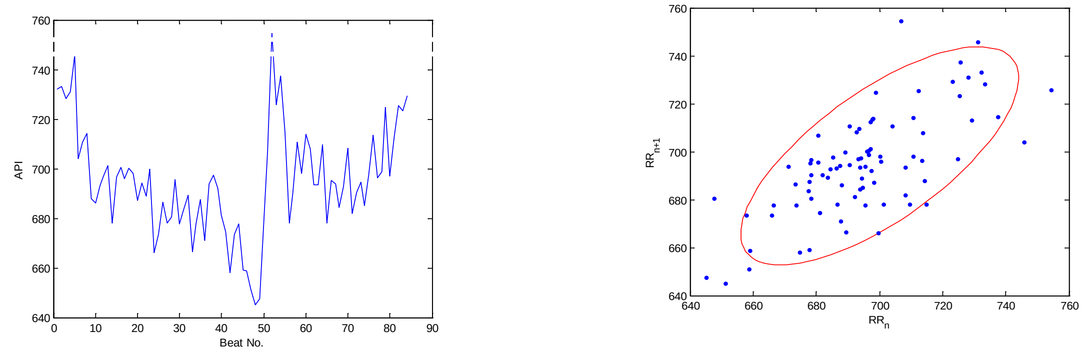


(b)Subject 2

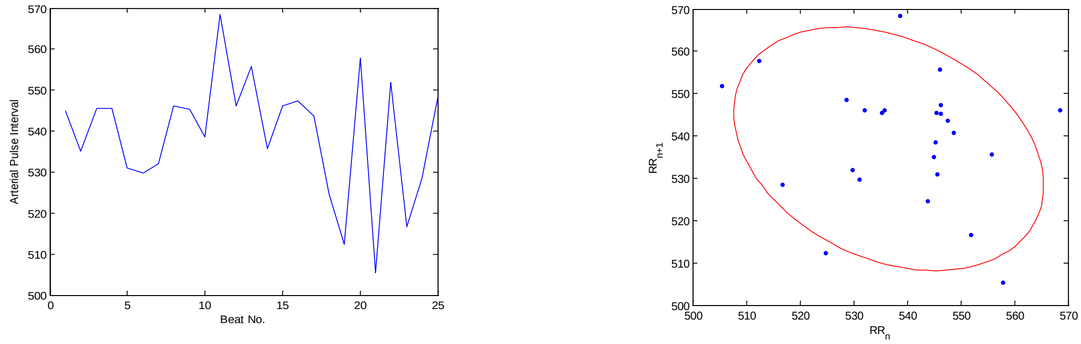


(c) Subject 3

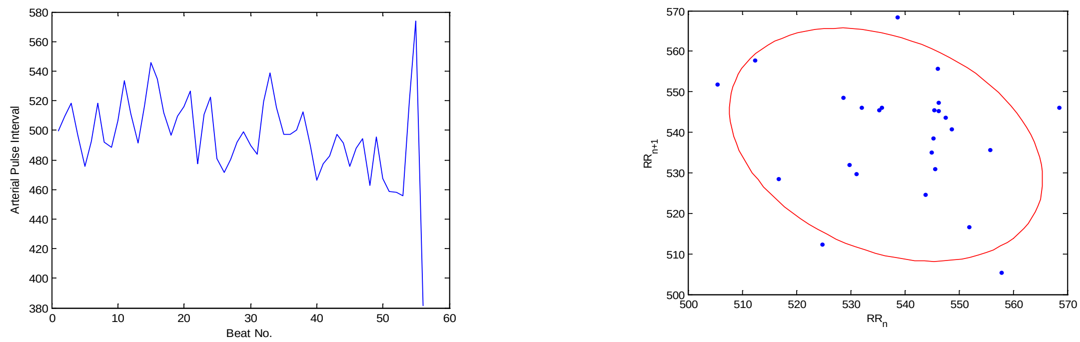
Fig. 3.11: API signal and Poincare plot for *Pitta* type pulses.



(a) Subject1



(b) Subject2



(c) Subject3

Fig.3.12: API signal and Poincare plot for *Kapha* type pulses.

From the above figures it can be seen that the results obtained in this work are similar to the ones reported by Joshi et al (6). The Poincare plots are similar except for two *Kapha* identified subjects [Fig.3.12 (b and c)]. The reason for this is not known. More investigations are necessary for this purpose. In order to see any differences in Poincare plot characteristics of *Vata, Pitta and Kapha* identified subjects ratios of SD1/SD2 for three types of pulses were calculated from the obtained Poincare plots. These are shown in Table 3.1

Table 3.1: The ratio SD1/SD2

Subject no.	*Vata*	*Pitta*	*Kapha*
1	0.4808	0.6357	0.4079
2	0.4065	0.6261	0.7319
3	0.5064	0.5248	0.1846

It can be seen that the ratios are random and no specific trend is seen. It is possible that this is a characteristic of the individual. However, collection of a large amount of data and its analysis is necessary before giving any conclusive remarks.

3.2.3 Analysis Based on Amplitude Ratio of Frequency Components

Fast Fourier Transform of the obtained signal of the obtained pulses was taken and analysis was done on the basis of ratio of amplitudes of the fundamental frequency and the secondary harmonics. a_1, a_2 and a_3 are denoted as the amplitudes of the fundamental, second harmonic and third harmonic frequencies.

The ratio a_1/a_2: It is the ratio of amplitude of fundamental frequency to the second harmonic. Mean of amplitude ratio a_1/a_2 for *Vata, Pitta and Kapha* type subjects was calculated. Fig.3.13 shows the bar graph of mean a_1/a_2.

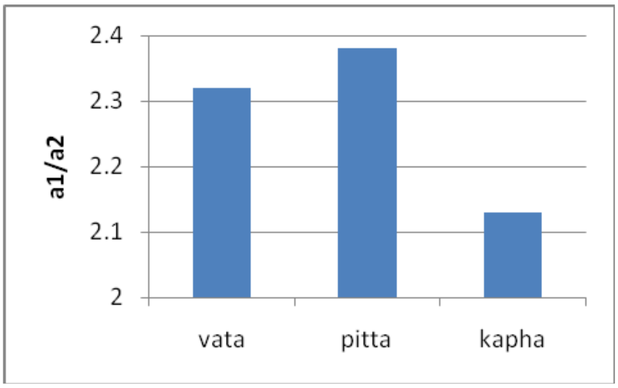


Fig. 3.13: Bar graph of mean a_1/a_2

It is observed that *Kapha* dominant pulses are having lower value of a_1/a_2 than *Pitta* and *Vata* type. *Vata* has moderate value whereas *Pitta* dominant pulses show maximum value of a_1/a_2. The parameter a_1/a_2 of *Vata* pulse is 2.28 ±0.71, which of *Pitta* pulse is 2.38 ± 0.64 and that of *Kapha* pulse is 2.13 ± 0.63. Statistical comparison shows that there is no significant difference between *Vata, Pitta* and *Kapha* pulses at the 0.05 level. To the best of author's knowledge no such data is available in the literature for comparison.

The ratio a_1/a_3: It is the ratio of amplitude of fundamental frequency to the second harmonic. Mean amplitude ratio a_1/a_3 for *Vata, Pitta* and *Kapha* type subjects was calculated. Fig.3.14 shows the bar graph of a_1/a_3. It is observed that *Kapha* dominant pulses are having lower value of a_1/a_3 than *Pitta* and *Vata* type. *Pitta* has moderate value whereas *Vata* dominant pulses show maximum value of a_1/a_3. The parameter a_1/a_3 of *Vata* pulse is 5.39 ±2.08, which of *Pitta* pulse is 4.96±3.63 and that of *Kapha* pulse is 4.8 ±1.87. Statistical comparison shows that there is no significant difference between *Vata, Pitta* and *Kapha* pulse at the 0.05 level.

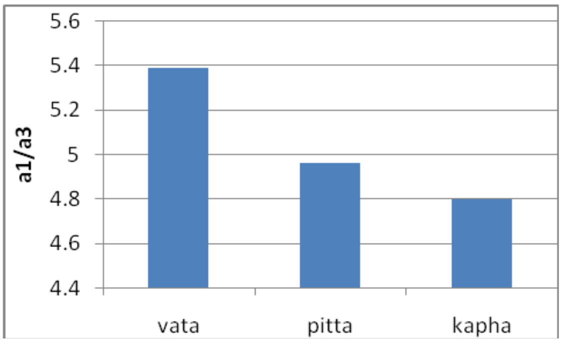


Fig. 3.14: Bar graph of parameter a_1/a_3

Statistical analysis of the ratio a_1/a_2 and a_1/a_3 shows that there is no difference between these parameter for *Vata, Pitta* and *Kapha* pulses and therefore these parameters are not of much use for classification of dominant *dosha*. However, large data need to be collected before making any conclusive remarks.

3.2.4 Time Domain Analysis of Pulse Waveform

Time domain analysis of the collected pulse waveforms was carried out. Various amplitude and time parameters of the pulse waveform were defined in article 1.2 of Chapter 1 [4, 5]. The same is repeated here in Fig. 3.15(a) for convenience.

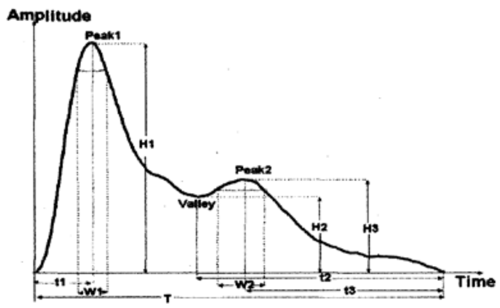


Fig. 3.15(a): Typical Radial pulse waveform [4].

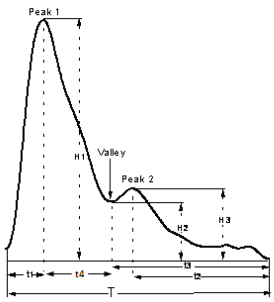


Fig. 3.15(b): Typical recorded pulse waveform using *"Nadi Parikshan Yantra"*

P1, P2 and V are the heights of percussion wave, dicrotic wave and valley in pulse measured from baseline respectively. The parameter t1, t2 and t3 are their respective time value. T is the period of pulse. Typical recorded pulse waveform using the "*Nadi Parikshan Yantra*" is shown in Fig. 3.15(b). It is similar to expected one [Fig. 3.15(a)]. Parameters P2/ P1, t2, t3 and T were measured for all the pulse samples collected from 100 subjects. The mean values of these parameters for *Vata*, *Pitta* and *Kapha* type of pulses (as per the diagnosis of *Nadi vaidya*) are calculated and are tabulated in Table 3.2.

Table 3.2: P2/P1, t2, t3 are T calculated for *Vata*, *Pitta* and *Kapha* type of pulses

Parameter	Dominant *dosha*			significant difference at the 0.05 level between		
	Vata	*Pitta*	*Kapha*	*Vata-Pitta*	*Pitta-Kapha*	*Vata-Kapha*
P2/ P1	0.36 ±0.08	0.40 ±0.09	0.26 ±0.07	yes	yes	yes
t_2	0.372 ±0.11	0.381 ±0.14	0.273 ±0.07	no	yes	yes
t_3	0.443 ± 0.10	0.445 ±0.14	0.336 ±0.07	no	yes	yes
T	0.7693 ±0.10	0.8227 ±0.3543	0.6810 ±0.08	no	no	yes

Statistical comparison using t-test was carried out between the three types of *doshas*. The obtained differences at the 0.05 level between *Vata-Pitta*, *Pitta-Kapha* and *Vata-Kapha* is shown in Table 3.2. If there is a significant difference at 0.05 level it is denoted by 'yes' and if there is no difference it is denoted by 'no'. It can be seen that the significant difference is seen in all the three combinations in case of ratio P2/P1. Other parameters show significant difference only in one or two combinations. Therefore it may be possible to use ratio P2/P1 only for classification. It is also necessary to collect large data before reaching any conclusion.

3.2.5 Analysis on the Basis Of Radial Pulse Shape

Pulse shape changes as a function of age are studied (8). Ratios t4/T, V/P1 and P2/P1 were calculated from the data collected from 82 subjects. Please refer Fig.3.15 (b) for definitions of various parameters. Fig. 3.16 (a) shows the graph t4/T as a function of age. As it can be seen that t4/T tends to increase with age. Fig. 3.16 (b) shows the age dependence of the ratio V/P1. It can be seen that there is no strongly pronounced relationship. The ratio V/P1 slightly increases with age. Fig. 3.16 (c) shows the age dependence of the ratio P2/P1. A slight increase in the ratio occurs with a decrease in the age.

In all these figures large scatter in data is observed for subjects in the age group between 20 to 30 years. It may be mentioned that there were large number of subjects in this age group and therefore the data is concentrated at the lower age group.

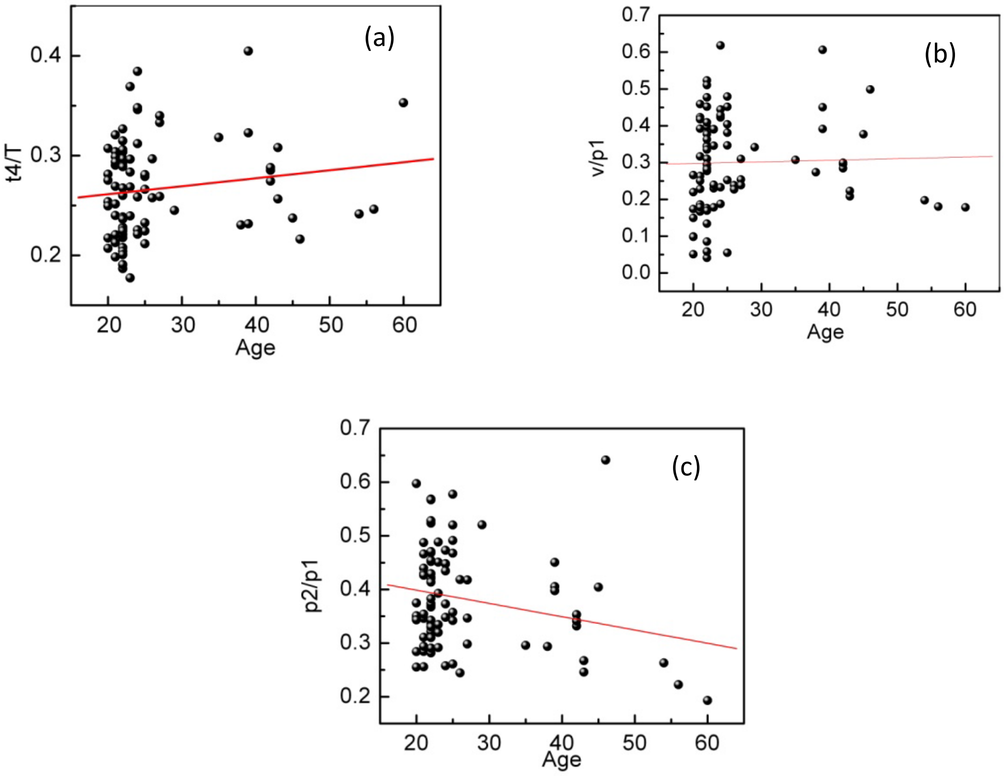


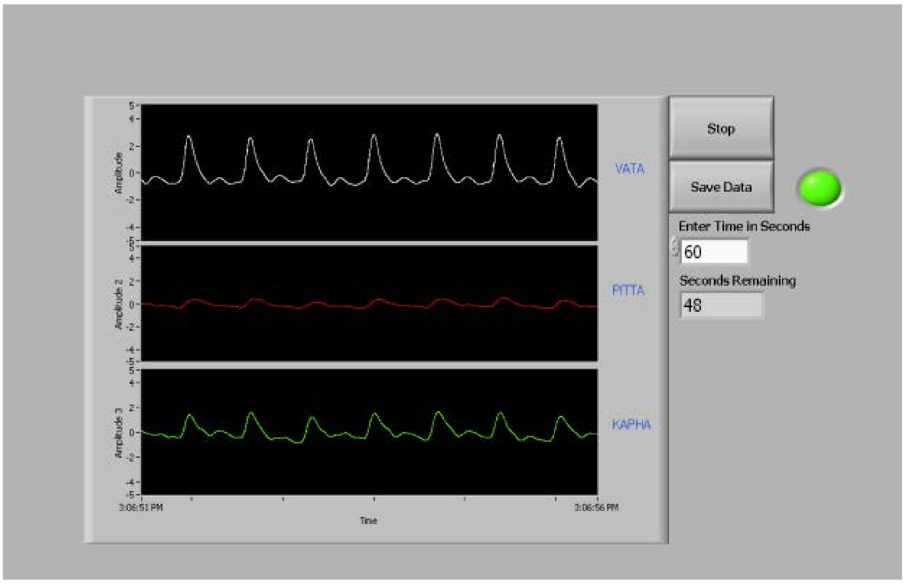
Fig. 3.16 (a): The relationship between t4/T and age. (b) The relationship between V/P1 and age. (c) The relationship between P2/P1 and age.

Differences in the ratios P2/P1, t_4/T and V/P1 between age groups were compared using the statistical program ANOVA. This analysis tool performs a simple analysis of Variance (ANOVA). As a result all three ratios were significantly different in terms of statistics at $p<0.05$. This indicates that ratios P2/P1, t_2/t_1 and V/P1 can be used to analyze distensibility of arteries.

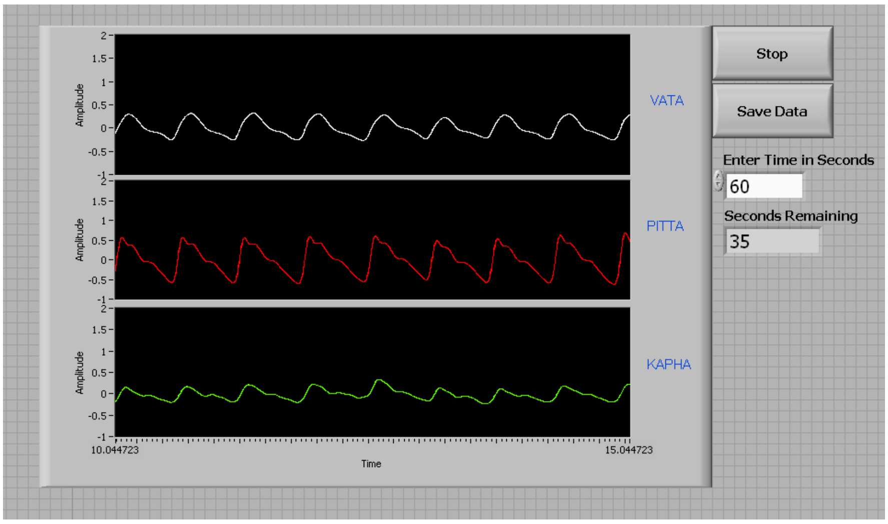
Hlimonenko et al (8) did the similar analysis on the radial pulse data obtained using Photoplethysmograph. Different trends of corresponding parameters as a function of age were observed by were observed by Hlimonenko et al. They also used statistical program ANOVA for analysis of their results. In their case only two ratios t_2/t_1 (corresponding to t_4/T in our case) and V/P1 are significantly different at $p<0.05$. Authors have correlated these ratios with the stiffness of artery and suggest that this type of analysis can provide simple inexpensive and noninvasive means for studying changes in the elastic properties of the vascular system. Though a large number of results are taken in the present studies they are not matching in all respects with the results reported by Hlimonenko et al. More detailed studies are needed before coming to any conclusion.

3.3 Results on Three Point Radial Pulse Measurement

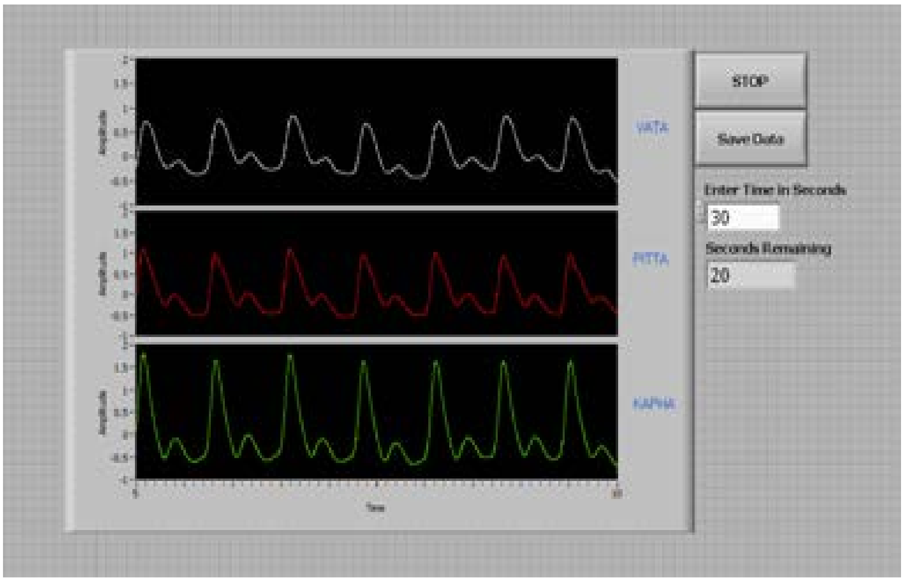
It is known that the *Nadi Vaidya* senses the pulse at three points on the radial artery. The sensor used for single point pulse measurement available to us was large in size (dia. = 22mm) and the typical size of *Nadi Vaidya'*s fingers is about 8mm to 1 cm. As an alternative to the above mentioned sensors, as described in article 2.3, the commercially available ultrasonic sensors of size 8 mm for three point measurements were used. Three sensors of identical characteristics are mounted on single strip (see Fig.3.14 (b)) and pulse recording was done simultaneously at three points. Same pressure between 40 to 80 mm of Hg (See article 3.1.4) was applied on the three pulse transducers. The data of 120 subjects of normal health was collected. Same subjects were checked by *Nadi Vaidya* to predict dominance of *dosha.* Typical waveforms obtained using *"Nadi Parikshan Yantra"* is shown in Fig. 3.17(a-c).



(a) ***Vata* dominant pulse**



(b)*Pitta* Dominant pulse



(c) *Kapha* dominant pulse

Fig.3.17: Typical pulse waveforms at three pulse points.

Fig.3.16 [a-c] show radial pulse waveforms of the subjects identified as *Vata, Pitta and Kapha pradhan* respectively. In the figures, the top waveform, in all the three screens, taken is at *Vata* point, middle one is from *Pitta* point and lower on is from *kapha* point. It can be seen that the amplitudes of the waveforms seen at *Vata, Pitta and Kapha* points on the radial artery are higher for *Vata, pitta and kapha* pradhan subjects respectively than at other two points. Similar were the observations for most of the other subjects also. Therefore, it can be said that difference in the amplitude of the pulses at three points can be used for classification of the *dosha*s in the subjects. *Nadi Vaidya*, further classified the subjects into 7 types *Vata, Pitta, Kapha, Vata-*

Pitta, Vata-Kapha, Pitta-Kapha, Vata-Pitta-kapha (Tridosh) pradhan dosha. Pradhan *dosha* was also identified from the relative amplitudes at the three points. Fig. 3.17 shows the results of the *Nadi Vaidya's* predictions and on the basis of amplitudes of *Vata, Pitta and Kapha* pulses and their combination taken using *"Nadi Parikshan Yantra"* .

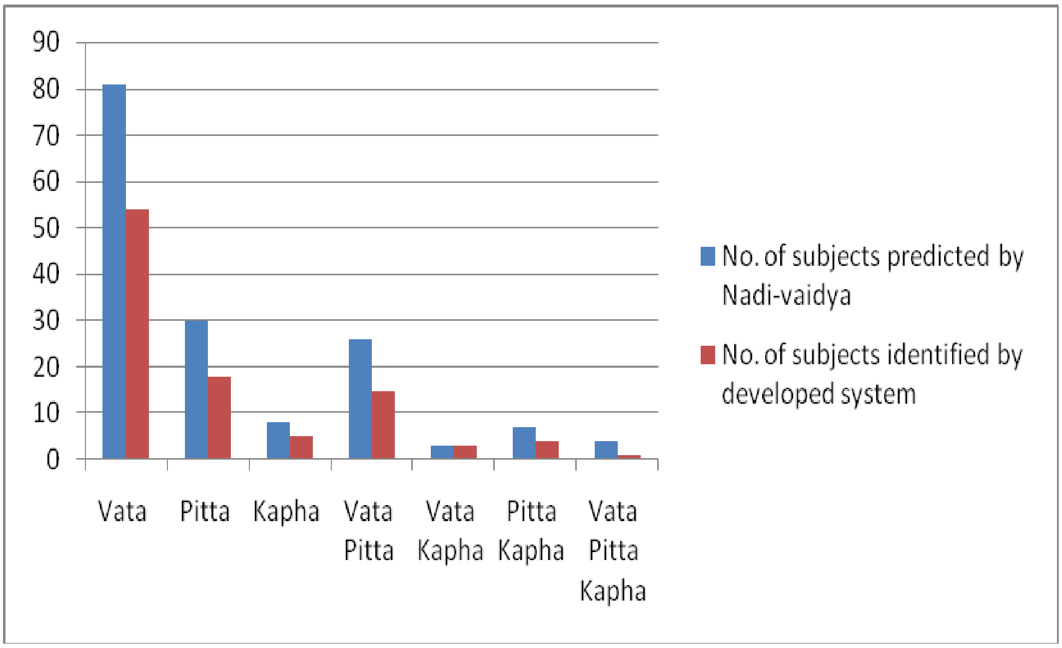


Fig. 3.17: Comparison of *Nadi-vaidya's* prediction and *Nadi Parikshan Yantra.*

The results of the *Nadi Parikshan Yantra* and *Nadi Vaidya's* predictions are 62% in agreement. It indicates that it is feasible to find the *pradhan dosha* on the basis of pressure pulse amplitudes. Collection of a large amount of data and proper statistical analysis is necessary for increasing the accuracy of predictions.

3.4 Conclusion

Large number of radial pulse data was collected using "*Nadi Parikshan Yantra*" developed in the present work. The same subjects were examined by *Nadi Vaidya* (Ayurvedic Physician). The data was collected from single pulse point (at *pradhan dosha* point) and three pulse points *(Vata*, *Pitta* and *Kapha)*. The radial pulse data collected from single pulse point was analyzed in frequency and time domains. It was observed that the parameter P2/P1 might be used to differentiate *Vata, Pitta* and *Kapha* whereas other parameters show no significant difference.

Radial pulse waveform data was also collected from three pulse points simultaneously on the radial artery. Feasibility is shown for using relative amplitudes of waveforms for identifying the *pradhan dosha* for the subjects. It may be mentioned that to the best of author's knowledge this type of analysis on the basis of relative amplitudes is reported for the first time.

References

1) Vasant D. Lad. Secrets of the Pulse: The ancient Art of Ayurvedic Pulse Diagnosis. Motilal Banarsidass (2005).
2) Young-Zoon Yoon, Myeong-Hwa Lee and Kwang-Sub Soh. Pulse type classification by varying contact pressure. IEEE Engineering in Medicine and Biology (2000), 106.
3) S. Upadhyaya, NadiVijnaana , 1st Edition, Vedic Life Sciences Pvt. Ltd., 1986
4) Wang KQ, Xu LS, Zhang D, Shi C. TCPD based pulse monitoring and analyzing. P*roceedings of the International Conference on Machine Learning and Cybernetics*. 2002;3:1366–1370.
5) B.H. Wang, J.L. Xiang. Detecting system and power spectral analysis of pulse signals of human body. Proceedings of ICSP1998. (1998), 1646.
6) Aniruddha J. Joshi, SharatChandran. V. K. Jayaraman, B. D. Kulkarni “arterial pulse rate variability Analysis for Dignoses” ICPR 2008
7) H.Wang P. Zhang . A Quantitative Method for Pulse Strength Classification Based on Decision Tree . JOURNAL OF SOFTWARE, VOL. 4, NO. 4, (2009)
8) Hlimonenko, I., Meigas, K., Vahisalu, R. Waveform analysis of peripheral pulse wave detected in the finger tip with photoplethysmograph. Meas. Sci. Rev. 3, (2003), 49.

FUTURE SCOPE

Future Scope

After successful development of "*Nadi Prikshan Yantra*" and establishing its feasibility for classification of dominant (*Pradhan*) *doshas* we propose to do the following

1. **Indigenous development of micro sensors tailored for human pulse detection and their packaging**

For the work presented in the thesis two types of piezoelectric sensors – MLT 1010 (commercially available for pulse detection) and piezoelectric based ultrasonic based ultrasonic sensors – were used. MLT 1010 has a good sensitivity, an appropriate frequency response but it is very large in size, and, therefore, it may not be suitable for three pulse point measurements. Ultrasonic sensors have an appropriate size and a good sensitivity but their frequency response is not much suitable for the present application. So the sensor is made flexible it will be more useful.

We, therefore, need to fabricate tailor made sensors for accurate monitoring for pulse data. This needs tailoring of dimensions, sensitivity and frequency response of the sensors. Piezoelectric sensors based on PVDF and PZT thin films are planned to be developed in MEMS technology.

Similarly packaging of the developed sensors suitable for use on the wrist of the human beings of different age and physique needs to be addressed. This will be done through the development of robotic hand.

2. **Pulse data collection and analysis of disease**

During our study it has been observed that the pulse shape, amplitude, frequency and relative positions of systolic and diastolic peaks and other parameters depend upon the age, health, and constitution etc. of an individual. It is, therefore, necessary to collect large amount of data and carry out the statistical analysis in order to generate the diagnosis report. Software will be developed for this purpose. Following tasks will be done during disease diagnosis.

(a) Coordination of clinical activities (patient examination, pulse data collection)

(b) Pulse data collection using "*Nadi Parikshan Yantra*"

(c) Development of analytical tools based on instrument and clinical data

(d) Exploration of pulse and clinical parameters to define diagnostic algorithms

(e) Development of Decision Support System based on diagnostic algorithm

(f) Integration of DSS and *"Nadi Parikshan Yantra"*

3. Understanding the formation of pulse and changes occurring due to disease using micro fluidics

Blood flow in arteries is dominated by unsteady flow phenomena. The cardiovascular system is an internal flow loop with multiple branches in which a complex liquid circulates. Normal arterial flow is laminar with secondary flows generated at curves and branches. The study of arterial blood flow will lead to the prediction of individual hemodynamic flows in any patient, the development of diagnostic tools to quantify disease, and the design of devices that mimic or alter blood flow. The study will allow us to give an insight into the development/generation of pulse, its flow dynamics and variation during disease outbreak.

Publications

International Journal

1. Abhay B. Joshi, Ashok E. Kalange, Dhananjay Bodas and S.A. Gangal "Simulations of piezoelectric pressure sensor for radial artery pulse measurement", Materials Science and Engineering: B Volume 168, Issues 1-3, 15 April 2010, Pages 250-253.

National Journals

1. A.E. Kalange and S.A. Gangal, "Piezoelectric Sensor for Human Pulse Detection" Defence Science Journal, Vol. 57, No. 1, January 2007, pp. 109-114, 2007.

2. A.E. Kalange and S.A. Gangal, "Data Acquisition system for Radial pulse detection using NI-DAQ card and Lab VIEW software" Jr. of Instrum. Soc. Of India, Vol 38 No. 4

3. Bhoopesh Mahale, A.E. Kalange and S.A. Gangal, "PC based human arterial pulse detection System", Jr. of Instrum. Soc. Of India, Vol 39 No. 4 (2009) pp 298-300.

Papers presented in conference

1. Kalange A E, Mahale B P, Gangal S A "NAdi-PArikshan Yantra:An Instrument for Pulse Examination" SENSORS-13, 13th National Seminar on Physics and Technology of Sensors, 2008.

2. Kalange A E, Mahale B P, Gangal S A "Effect of Contact pressure on Radial pulse." ICI-2009 & NSI-34, 2010

3. Mahale B P, Kalange A E, Gangal S A, "Comparison of responses of the ultrasonic sensors, PZT sensors and commercially available pulse sensors for detection of human arterial pulse." SENSOR-14, 14th National Seminar on Physics and Technology of Sensors, 2009.

4. Mahale B P, Kalange A E, Gangal S A "Non-Invasive Technique to Study Arterial Stiffness Characteristics Using Arterial Pressure Pulse". SENSOR-15, 15th National Seminar on Physics and Technology of Sensors, 2010.

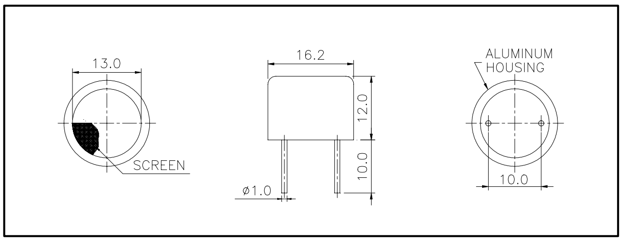
5. Kalange A.E. and Gangal S.A, "Radial pulse (nadi) detection system using Lab View" SENSOR-11, 11th National Seminar on Physics and Technology of Sensors, 2006.

6. A.E Kalange, (Mrs), Dr. Phadake A. A., Dr.H.R. Kulkarni and S. A. Gangal," Classification of Human pulse on the basis of Vata, Pitta and Kapha, using in-house developed pulse detection system." SENSORS-12, 12th National Seminar on Physics and Technology of Sensors, 2007.

7. Mahale B P, Kalange A E and Gangal S A " Design And Develpoment Of An EmbeddedSystem For Human Pulse Detection" SENSORS-13, 13th National Seminar on Physics and Technology of Sensors, 2008.

Air Ultrasonic Ceramic Transducers 400ST/R160

Dimensions: dimensions are in mm



Impedance/Phase Angle vs. Frequency

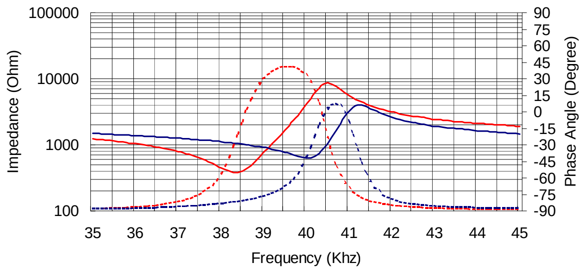
Tested under 1Vrms Oscillation Level

400SR160 Impedance

400SR160 Phase

400ST160 Impedance

400ST160 Phase



Specification

400ST160	Transmitter
400SR160	Receiver
Center Frequency	40.0±1.0Khz
Bandwidth (-6dB) 400ST160	2.0Khz
400SR160	2.5Khz
Transmitting Sound Pressure Level at 40.0Khz; 0dB re 0.0002µbar per 10Vrms at 30cm	120dB min.
Receiving Sensitivity at 40.0Khz 0dB = 1 volt/µbar	-65dB min.
Capacitance at 1Khz ±20%	2400 pF
Max. Driving Voltage (cont.)	20Vrms
Total Beam Angle -6dB	55° typical
Operation Temperature	-30 to 80°C
Storage Temperature	-40 to 85°C

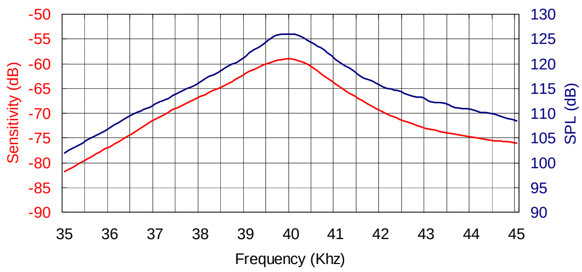
All specification taken typical at 25°C
Closer frequency tolerance can be supplied upon request.

Models available:

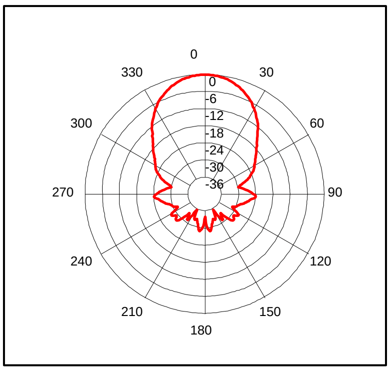
1	400ST/R160	Aluminum Housing
2	400ST/R16B	Black Al. Housing
3	400ST/R16P	Plastic Housing

Sensitivity/Sound Pressure Level

Tested under 10Vrms @30cm

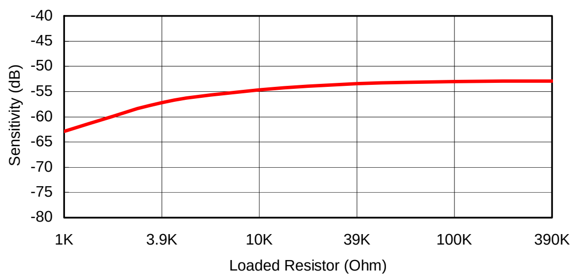


Beam Angle: Tested at 40.0Khz frequency

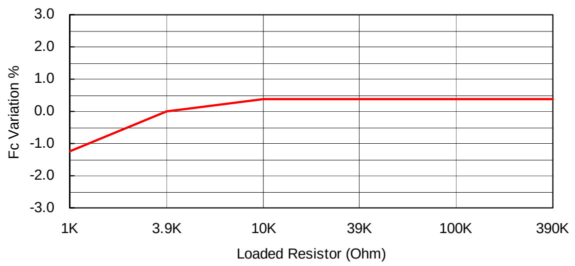


400SR160 Receiver

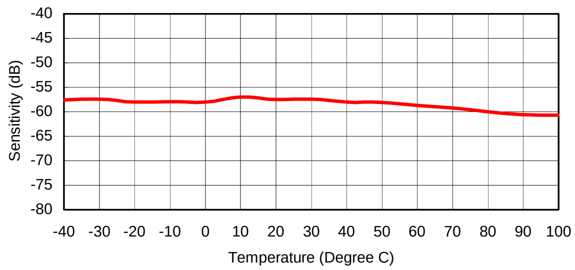
Sensitivity Variation vs. Loaded Resistor



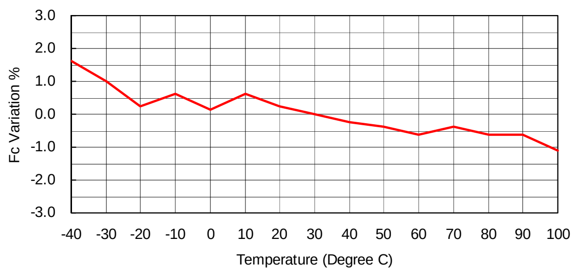
Center Frequency Shift vs. Loaded Resistor



Sensitivity Variation vs. Temperature

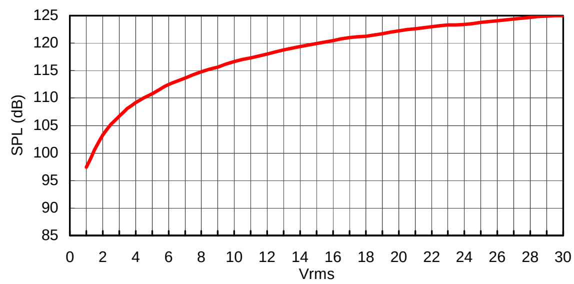


Center Frequency Shift vs. Temperature

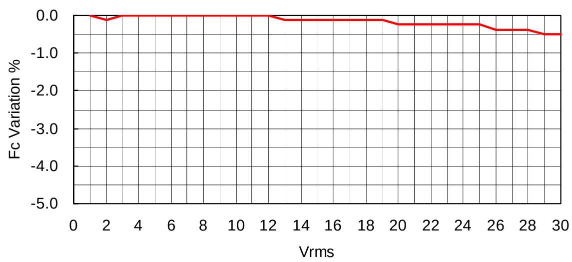


400ST160 Transmitter

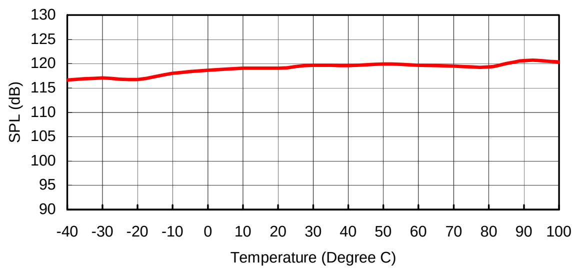
SPL Variation vs. Driving Voltage



Center Frequency Shift vs. Driving Voltage



SPL Variation vs. Temperature



Center Frequency Shift vs. Temperature