

Photoplethysmography: Design, Development, Analysis and Applications in Clinical and Physiological Measurement – A Review

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ABSTRACT: Photoplethysmography is a non-invasive, electro-optical technique for detecting the cardiovascular pulse wave generated by elastic nature of the peripheral vascular arteries by the contraction of heart. Photoplethysmogram (PPG), a pulse wave generated varies in accordance to blood volume changes in the microvascular bed of a tissue. This review paper emphasizes on the earlier works on the design and development of data acquisition system, analysis methods and applications of PPG. Based on the research gaps from review, in the present work a ZigBee based wireless PPG system for real time monitoring and assessment of cardiovascular and respiratory systems has been designed and developed. The PPG signals recorded from 25 normal subjects and 20 cardiac patients from the index finger. Pulse rate (PR), average pulse rate (APR) pulse rate variability (PRV) and spectral analysis is carried out on acquired PPG signals using Matlab. The study and results shows PPG can be an alternative to the traditional methods.

KEYWORDS: Photoplethysmography, Electrocardiography, pulse rate variability, Heart rate variability, cardiovascular system, frequency spectrum, pulse transit time

I. INTRODUCTION

Photoplethysmography is a simple, low cost, non-invasive optical technique that can used to detect blood volume changes in the microvascular bed of tissue. The main peripheral sites where the PPG can be obtained are the tissue pads of the fingers, ears and toes, having high degree of superficial vasculature. With each heart beat a pulse radiates out to the peripheral circulation. The characteristics of these pulses are unique and are influenced by arterial ageing and diseases [1]. These pulses can be detected non-invasively using PPG system. The measurement of blood volumetric changes in the skin perfusion by means of PPG depends on the fact that blood absorbs ultra red/infrared light more strongly than skin, tissues and fluids [2]. The change in blood volume caused by the pressure pulse can be detected by illuminating the skin from a light source and measuring the amount of light transmitted to a photodetector [3]. The signal obtained from the photodetector is related to pulsatile arterial blood volume changes and the signal is called as PPG. The detected PPG signal helps in determining the properties of the vascular tissue, peripheral blood circulation, and cardiac activity during the cardiac cycle and the respiratory related ailments.

The PPG signal is complex and comprises a pulsatile components (AC signal) attributed to synchronous changes in the blood volume with each heart beat and is superimposed on a slowly varying baseline (DC signal) with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation [4]. The complex PPG signals can provide valuable information about cardiovascular and respiratory systems. The PPG technique becoming popular in recent years, because of the following reasons; (i) measurement of physiological parameters without the need of electrodes, (ii) portable technology for the primary care and community based clinical settings, (iii) use of simple, low cost and compact semiconductor devices, and (iv) advanced in computer-based pulse wave analysis techniques. The PPG technology is widely used in commercially available medical devices for

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measuring oxygen saturation (SpO_2), blood pressure (BP), cardiac output (CO), and assessing autonomic function and also for detecting peripheral vascular disease [5]. The studies reveal the differences in the characteristics of PPG signals such as pulse timing, amplitude and shape features in accordance with the changes in blood volume. Thus by studying the pressure pulses the important information about the cardiovascular mechanism can be extracted. Monitoring the peripheral pulse is more useful and dependable than monitoring the HR derived from the ECG in the case of a heart block because it can immediately indicate the cessation of blood circulation in the limb terminals. Moreover, a photoelectric pick-up transducer is much easier to apply than the three ECG electrodes. The amplitude of the PPG signal obtained is also quite large as compared to the ECG signal and gives better signal-to-noise ratio [6]. The PRV derived from PPG is compared with HRV derived from ECG and observed that PPG technique gives accurate results [7]. However, the technique is severely subject to motion artifacts, noises which may degrade the PPG signals and need to be taken care by using suitable technique [8], [9].

This review paper describes early and recent history of PPG, basic principle of operation and interaction of light with tissue, design and development of system, recording and analysis of pulse waveforms. Based on the important findings and research gaps, an accurate and reliable PPG system has been developed in the present work which can be effectively used for handicapped patients, ambulatory conditions and post operative care unit for continuous monitoring and assessment of cardiovascular and respiratory systems. The acquired PPG signal is analyzed to quantify pulse rate, average pulse rate, pulse rate variability and frequency components of subjects using Matlab [10], [11]. Further, PPG system also updated using ZigBee wireless technology for remote monitoring and assessment of health condition of patients in real-time.

II. LITERATURE REVIEW

The photoplethysmograph is a non-invasive electro-optical signal to measure pulsations associated with changes in volume of blood flow in the peripherals of human body [12]. In 1936 Molitor and Kniazuk of the Merck Institute of Therapeutic Research, New Jersey, described an instrument used to monitor the blood volume changes in the rabbit ear following venous occlusion with administration of vasoactive drugs. They also described recordings made with a reflection mode PPG system from human fingers [13]. In the year 1937 PPG technique was introduced by Hertzman and his colleagues. They published their first paper on PPG describing the use of a reflection mode system to measure blood volume changes in the fingers induced by the Valsalva manoeuvre, exercise and with exposure to cold. Their contribution to the field demonstrated the potential clinical utility of this technique. In 1938, Hertzman undertook a validation of the PPG technique by comparing blood volume changes with those measured simultaneously by mechanical plethysmography [14]. Preliminary observations on the PPG technique were also reported in the year 1938 by Matthes and Hauss. Hertzman and Dillon in 1940a separated the AC and DC components of PPG with filters and electronic amplifiers and monitored vasomotor activity [15]. The potential sources of error with the technique have been identified by Hertzman, who emphasized that good contact with skin was needed, but without excessive pressure that would result in blanching, and advised that movement of the measurement probe against the skin should be avoided. These observations led to the development of elaborate positioning of devices. Hertzman identified illumination is also an important design consideration and used a battery powered torch bulb which has relatively wide spectrum. He emphasized that the widespread illumination can mix skin microvascular blood flow with larger vessel signals. Furthermore, constant light intensity could not be guaranteed [14]. The principle of indirect continuous monitoring of BP waveform is unloading technique. This method was based on idea that if an externally applied pressure in the cuff is equal to the arterial pressure instantaneously, the arterial walls will be unloaded (zero transmural pressure) and the arteries will not change in size. In this condition, the blood volume will not change. This method was an attempt to realize for the first time by Penaz in the year 1973 using photoelectric technique of detecting blood flow, equipped with a transparent inflatable cuff controlled by a servocontrol system in the human finger [16]. In recent decades the desire for small, reliable, low-cost and simple-to-use, noninvasive cardiovascular assessment techniques are key factors that have helped in development of PPG technique. Advances in opto-electronics and clinical instrumentation have also significantly contributed to its advancement. The developments in semiconductor technology, i.e. light emitting diodes (LED), photodiodes and phototransistors, have made considerable improvements in the size, sensitivity, portability, reliability and reproducibility of PPG probe design. A major advance in the clinical use of a

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PPG based technology came with the introduction of the pulse oximeter as a non-invasive method for monitoring patient's arterial oxygen saturation [17].

2.1 Photoplethysmography

2.1.1. The Photoplethysmography waveform

The fundamental frequency of pulsatile component (AC signal) of the PPG waveform is typically around 1.2 Hz, depending on HR. This AC component is superimposed onto a large quasi-DC component that relates to the tissues and to the average blood volume. This DC component varies slowly due to respiration, vasomotor activity and vasoconstrictor waves, and also thermoregulation [18], [19]. The characteristics of PPG signals are also body site dependent [12]. With suitable electronic filtering and amplification both the AC and DC can be extracted for subsequent pulse wave analysis.

2.1.2. Optical Considerations in the Origin of PPG Waveform

The interaction of light with biological tissue is complex and includes the optical processes such as scattering, absorption, reflection, transmission and fluorescence [20]. According to researchers the key factors of the optical processes in relation to PPG measurements that can affect the amount of light received by the photodetector are the blood volume, blood vessel wall movement and the orientation of red blood cells (RBC) [21]. In 2006 Naslund et al. detected pulsatile waveforms in the bone shows direct relationship with perfusion, and the greater the blood volume the more the light intensity is attenuated [22]. The wavelength of optical radiation is also important in light-tissue interactions for three reasons [23]. (i) The optical water window: the main constituent of tissue is water that absorbs light very strongly in the ultraviolet and the longer infrared wavelengths. The shorter wavelengths of light are also strongly absorbed by melanin. There is, however, a window in the absorption spectra of water that allows visible (red) and near infrared light to pass more easily, thereby facilitating the measurement of blood flow or volume at these wavelengths. Thus, the red or near infrared wavelengths are often chosen for the PPG light source [24]. (ii) Isobestic wavelength: Differences exist in absorption between oxyhaemoglobin (HbO_2) and reduced haemoglobin (Hb) except at the isobestic wavelengths [25]. For measurements performed at an isobestic wavelength close to 805 nm, for near infrared range the signal should be largely unaffected by changes in blood oxygen saturation, and (iii) Tissue penetration depth: the depth to which light penetrates the tissue for a given intensity of optical radiation depends on the operating wavelength [26]. The PPG can provide information about capillary nutritional blood flow and the thermoregulatory blood flow through arterio-venous anastomosis shunt vessels.

2.1.3. Reproducibility of Signal

The factors which affect the reproducibility of PPG signal includes the method of probe attachment to tissue, probe-tissue interface pressure, pulse amplifier bandwidth, minimization of movement artifact, subject posture and relaxation, breathing, wakefulness, room temperature and acclimatization [27], [28]. In 1988 Jago and Murray addressed the uncertainty in PPG measurements for a group of healthy adult subjects. They studied the repeatability of PPG pulse transit time (PTT) measurements made from the ear, thumb and toe sites both within session and between sessions held on separate days. Measurements at individual sites and bilateral (right-left) side differences were both assessed. The results showed the importance of controlling factors such as posture, ambient temperature, relaxation and acclimatization. Bilateral measurements were generally more repeatable than individual site measurements since HR, respiration and BP factors tend to affect both sides of the body simultaneously [29].

2.1.4. Pulse Wave Characterization.

The PPG pulse shown in Fig.1 has two phases, the anacrotic phase being the rising edge of the pulse, and the catacrotic phase being the falling edge of the pulse. The anacrotic phase is primarily concerned with systole and catacrotic phase with diastole and wave reflections from the periphery [3]. A dicrotic wave is usually seen in catacrotic phase of healthy subjects due to closer of semilunar valve and artery wall. It is useful also to consider the BP pulse and its propagation along individual arteries.

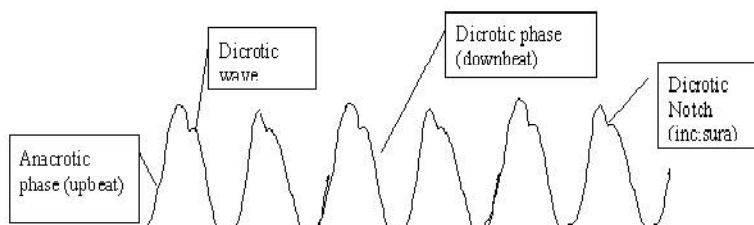


Fig.1 Typical PPG waveforms free of artefact

The pressure pulse wave moves towards the periphery undergoes amplification and alterations in its shape and temporal characteristics. These changes are thought to be largely due to reflection of the pulse wave and the tapering down of the arteries towards the periphery. Pulse propagation in arteries is further complicated by frequency dependent phase distortion [30].

In 1940b, Hertzman and Dillon compared PPG to mechanical plethysmography in arteriopathies and in normal control subjects [31]. They derived a crest time measurement from the rising edge of the pulse waveform and normalized it to the HR. The crest time was prolonged in patients with vascular disease or hypertension and features such as beat-to-beat PPG rise time, PTT, amplitude, shape, and the variability in each of these have been investigated [32]. The pulse landmarks shown in Fig.2 can be automatically identified and analyzed using computer to give beat-to-beat pulse transit time to the foot of the pulse (PTTf), pulse transit time to the peak of the pulse (PTTp), and foot-to-peak amplitude (AMP), and these can be used to calculate the normalized pulse contour.

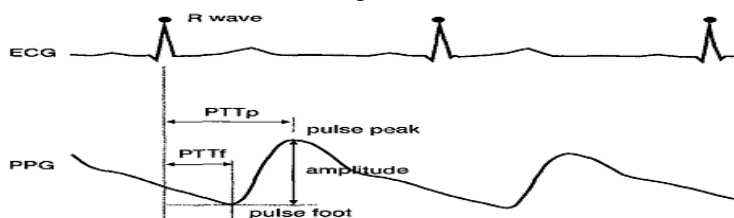


Fig.2 ECG with characterization of PPG pulse timing, amplitude and shape features

III. CLINICAL APPLICATIONS

PPG has been widely used in clinical physiological monitoring of parameters such as blood oxygen saturation, blood pressure, heart rate, heart rate variability, cardiac output, and respiration, vascular assessment such as arterial disease, arterial compliance and ageing, endothelial function, venous assessment, vasospastic conditions, and autonomic functions like vasomotor function and thermoregulation, orthostatic intolerance, neurology and other cardiovascular variability assessments. This section reviews each of these areas in brief.

3.1 Clinical Physiological Monitoring

3.1.1 Blood Oxygen Saturation.

Pulse oximetry utilizes PPG measurements to obtain information about the arterial blood oxygen saturation (SpO_2) as well as HR [33]. SpO_2 can be determined by using ultra red and near infrared light through vascular tissue, with rapid switching between the wavelengths. The amplitudes of the red and near infrared AC signals are sensitive to changes in SpO_2 because of the differences in the light absorption of HbO_2 and Hb. From their amplitude ratio and corresponding PPG DC components SpO_2 can be measured with the assumption that AC component of PPG solely from the arterial blood changes with each heart beat. In the year 2006 Kyriacou observed the limitations of pulse oximetry are that the peripheral pulse to be present, SpO_2 readings can be affected by dyshaemoglobinaemias, and its accuracy can fall off at

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low saturation levels. He suggested that using advanced algorithms the problem of movement artifact affecting the measurement can be reduced [34]. Pulse oximeters measure SpO₂ using both reflection and transmission modes.

3.1.2 Heart Rate (HR)

The HR is an important physiological parameter to measure in clinical settings, including hospital-based and ambulatory patient monitoring. The AC component of the PPG pulse is synchronous with heart beat can be a source of HR information. In pulse oximetry HR is often displayed alongside the SpO₂ level. The main problem with pulse oximetry is reduction in accuracy due to movement artifact or cardiac arrhythmia. Reliability of HR detection can be improved by using simple digital filtering and zero crossing detection through which HR and respiratory components can be separated from the PPG signal [35], [36]. Yousefi et al. proposed a novel real-time adaptive calculation for the accurate movement tolerant extraction of HR and oxygen saturation (SpO₂) from wearable PPG biosensors [37]. The proposed algorithm overcomes the motion artifacts arising from different sources including tissue impact and venous blood changes during body movements and gives commotion free PPG waveforms. A two-stage normalized least mean square adaptive noise canceller is designed and validated using a novel synthetic reference signal at each stage.

3.1.3 Cardiac Output (CO)

In healthy adult the volume of blood pumped by the heart is in the range of 5 liters per minute but can be impaired in patients with cardiovascular disease. Its accurate, reliable and non-invasive measurement is important clinically. Cardiac output can be estimated from PPG derived pulse contour analysis on a beat-by-beat basis (multiplying stroke volume with HR, CO = SV x HR). Many researchers used different techniques to estimate cardiac output and found no significant mean differences [38], [39], and suggested that Modelflow method is an accurate procedure to measure cardiac output in humans both at rest and during exercise and could be used for routine clinical purposes. The ModelFlow method is an estimation of stroke volume which utilizes a non-linear adaptive 3-element Windkessel model to mimic specific properties of the aortic input impedance to estimate aortic blood flow on a beat-by-beat basis.

3.1.4 Respiration

Respiration causes variations in peripheral circulation. The very low frequency components of the PPG signal indicates respiratory induced intensity variations (RIIV) and are well documented by Johansson et al. and Nilsson et al. RIIV includes contributions from the venous return to the heart caused by alterations in intra-thoracic pressure and also changes in the sympathetic tone control of cutaneous blood vessels [36], [40]. Changes in pulse timing characteristics with breathing have also been studied using PTT to track arousals during obstructive sleep apnoea, and leading to a clinically useful non-invasive measure of inspiratory effort in patients with sleep-related breathing disorders [41]. Slow paced breathing and deep inspiratory gasp challenges in autonomic function testing can also induce significant changes in the PTT [42].

3.2 Vascular Assessment

3.2.1 Arterial Disease

Atherosclerosis is also called peripheral arterial occlusive disease (PAOD) is an intermittent claudication typically causes pain that occurs with physical activity which increases with ageing, especially from the fourth or fifth decade of life. PAOD is associated with increased risk of coronary artery disease and stroke, and even the relatively milder degrees of PAOD may interfere with the lifestyle and well-being of patients [43]. Multi-body site PPG measurements have been proposed for peripheral vascular disease detection. In 2000a, Allen and Murray demonstrated the considerable similarity in bilateral (right and left body side) PPG characteristics at three main peripheral sites, i.e. the ear lobes, thumb pads and great toe pads [44]. Objective assessment of vascular ageing is very important since arterial stiffness is associated with hypertension, a risk factor for stroke and for heart disease. The stiffer the artery the faster the pulse will travel to the periphery [45].

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3.2.2 Endothelial Function

The endothelium is the layer of thin specialized epithelium, comprising a single layer of cells that line the interior surface of blood vessels to form an interface between the circulating blood in the lumen and the vessel wall. Endothelial cells are involved in many aspects of vascular biology, including vasoconstriction and vasodilatation, blood clotting, atherosclerosis, angiogenesis, and inflammation and swelling. Endothelial dysfunction is considered to be an early event in atherosclerosis and correlates with major risk factors for cardiovascular disease.

Endothelial function can be assessed non-invasively by ultrasound brachial artery diameter measurement before and after several minutes of blood flow occlusion to the arm [46]. The change in arterial diameter gives a measure of flow mediated vasodilatation. The technique, however, is operator dependent and requires high cost ultrasound imaging instrumentation which could limit its usefulness for routine clinical assessments. PPG has also shown potential for the assessment of endothelial function and is less costly than the ultrasound approach. Shape-related information can be extracted from the PPG waveform to quantify vasodilatory effects with reactive hyperaemia. This analysis could include comparing the height of the reflected peak relative to the systolic peak or quantifying the degree of maximal pulse damping. In the year 1986 Lund demonstrated that the potential for PPG assessments to assess vasodilatation done using haemodynamic responses to nitroglycerin (NTG) therapy [47]. In the PPG measurement protocol was described whereby changes in the dicrotic notch feature of the finger and toe pulse were studied over several hours to give information about the degree and length of vasodilatation with vasoactive drug. Ruiz-Vega et al assess the effects of vasodilator therapy by comparing with relative height of the dicrotic notch in relation to foot-to-peak pulse amplitude over time [48]. Chowienczyk et al (1999) and Gopaul et al (2001) detected that the finger digital volume pulse (DVP) contour has the potential to help investigate endothelial-dependent dilatation in patients with type-II diabetes mellitus using PPG derived reflection index [49].

3.3.3 Vasospastic Condition

The vasospastic or cold sensitivity condition known as Raynaud's phenomenon, it has been investigated using different optical measurement techniques, including PPG. In the year 1985 Cooke et al (1985) characterized the PPG pulse shape in healthy subjects and Raynaud's patients and found that both the pulse amplitude and the slope of the rising edge were good markers for the condition [50]. They also reported the loss of the dicrotic notch in patients with Raynaud's secondary to systemic sclerosis and associated this with reductions in vessel compliance. Bogadi-Sara and Zavalic in the year 1996 studied the pulse amplitude changes with cold exposure and potential for assessing 'vibration white finger' (VWF), also known as hand arm vibration syndrome (HAVS) [51]. This approach can be extended to multi-channel finger PPG assessments [52].

3.3.4. Microvascular Blood Flow Tissue Viability

Many techniques have been proposed for the assessment of the microcirculation, including radioisotope clearance, infrared thermography, capillaroscopy, laser Doppler flowmetry, transcutaneous oxygen pressure, histology, spectrophotometry, ultrasonography, PPG and (non-contact) PPG imaging technology. The relative merits of these techniques can be studied from papers by Almond and Cooke, Midttun and Sejrsen, and Huelsbusch and Blazek [53], [54], [55].

Anatomy and physiology of microvascular blood flow is complex, with regional differences across the body for the nutritional and thermoregulatory vascular systems. Tur et al. (1983) studied the complexity of microvascular blood flow and quantified the basal perfusion of the microcirculation as a function of anatomic position for measurements collected from more than fifty skin surface sites of healthy subjects. Higher regions of perfusion were noted at the ears, fingers, palms and face [56]. The amplitude of the PPG pulse often correlated with laser Doppler blood flow. Jones et al in the year 2000 shown measurement of the tissue perfusion is important for the clinical assessments of viability and healing. Perfusion of oxygen-carrying blood is vital for the preservation of tissue. In plastic surgery the post-operative PPG monitoring of tissue perfusion can detect early problems in free tissue transfer enabling early intervention and salvage [57]. In the year 1991 Taha studied the interruption of blood supply to the tissues lead to pressure sores [58]. Potential of PPG as an objective measure of the healing potential of tissue was shown by Lee et al in the year 1979. If the PPG signal was pulsatile then healing was indicated with conservative management, if non-pulsatile then healing was likely to fail [59].

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3.3.5 Autonomic Function

PPG signal is composite in nature and has low frequency components relating to respiration, BP control and thermoregulation, as well as relating to the heart synchronous pulse waveform. There is considerable interest in the PPG technique applied to autonomic function including studying the variability of these signal components at the different body sites [60].

3.3.6 Vasomotor Function and Thermoregulation

Many researchers have focused their study on low frequency and spontaneous fluctuations of the PPG signal. A variety of pulse wave analysis techniques have been used, including power spectral and correlation analysis to characterize the beat-to-beat PPG amplitude variations attributed to sympathetic activity, as well as the left body side similarity in low frequency characteristics [11], [61]. Further, found that these fluctuations are linked to the sympathetic nervous system has been demonstrated by the increase in PTT following epidural anaesthesia treatment and the reduction in low frequency variability following thoracic sympathectomy. Nitzan et al. (1998a) and Buches et al. (2005) observed the degree of bilateral dissimilarity in the PPG low frequency characteristics for diabetic patients with neuropathy and has also been measured with the average right to left finger pulse low frequency baseline correlation significantly reduced from 0.93 in non-diabetic subjects to 0.78 in diabetic subjects, and the average right to left toe pulse low frequency baseline correlation significantly reduced from 0.93 to 0.81 [62]. Similar reductions in correlation were found for the pulse amplitude.

Autonomic characteristics of the PPG signal during anaesthesia have shown the relative stability of ear and finger waveforms measured at different stages of the procedure, with variability attributed to vasoconstrictor activity less apparent at the ear site. Larsen et al. in 1997 observed the spectral analysis of PPG at the ear and finger sites and compared with resting healthy subjects with patients undergoing anaesthesia. At rest majority of spectral analysis was in low frequency band (< 0.08 Hz) and found fluctuations are greater at the finger than at the ear. Low and mid frequency bands were reduced during anaesthesia but the high frequency band attributed to ventilation was maintained. Quantification of PPG waveforms in this way could help to better understand the physiological processes and stages during anaesthesia [63].

3.3.7 Blood Pressure (BP) and Heart Rate Variability (HRV)

The physiological control of HR and BP is very important in maintaining BP homeostasis, and is often characterized by the baroreflex sensitivity (BRS, unit ms/mmHg). BRS can be attenuated in cardiovascular disease. Its non-invasive assessment is possible using beat-to-beat peripheral arterial BP waveforms measured using PPG technology [16]. The HR and its variability are much more straightforward since they can easily be extracted from PPG pulse signals. As well as the deep inspiratory gasp challenge in autonomic function testing slow paced breathing can be performed. This exercise should induce periodic and synchronous BP (PPG pulse) and HR changes [64], [65].

The study by Drinnan et al. (2001) showed that PTT at the finger is clearly modulated by paced breathing (rate 0.1 Hz). He calculated the incremental PTT and RR interval values of ECG on a beat-to-beat basis using an overlapping waveform morphology technique and their variability summarized using simple statistics. The phase differences between the signals were calculated using cross correlation analysis and a strong relationship found overall, with changes in PTT lagging changes in RR by approximately 3 heartbeats [66].

3.3.8. Orthostasis

Changes in pulse with orthostatic stress have been assessed by several researchers. Nasimi et al. during 1991 investigated sympathetic neuropathy in patients with diabetes mellitus by monitoring PPG frequency characteristics throughout a supine-to-standing posture challenge [67]. A significant difference in the lower frequency components with standing was found in healthy subjects, but with less change detected in the patient group. In 1992 he also investigated periodic posture stimulation on local vasomotor reflexes by applying a periodically controlled pulley-tracked movement to the study leg and detected the entrainment across a range of frequencies by both finger and toe PPG, and largely independent of breathing input [68]. In 2006, Linder et al also investigated beat-to-beat changes in the ear and finger pulses on standing and have related these to HR dynamics. Orthostasis assessment is very important in military and space research [69].

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3.3.9. Neurology

Brain autonomic control is reported to be asymmetrical, with the left hemisphere affecting predominantly parasympathetic function and the right hemisphere affecting predominantly sympathetic function. In migraine patients autonomic function can be assessed by measuring the trigemino-parasympathetic reflex to vasodilator response at the forehead with bilateral PPG. In 2003, a study by Avnon et al., on patients with various migraine types [70], observed the cranial parasympathetic function differed among, with bilateral sufferers having the greatest amount of vasodilatation and unilateral sufferers the least. He also studied (2004) on left- and right-sided migraineurs outside migraine attacks and found that the left-sided group had significantly higher parasympathetic vasodilatation, although the somato-sympathetic vasoconstriction reflex at the finger was similar for both groups. PPG therefore shows considerable potential for neurological assessment, with the capability to give new insights into the physiology and pathophysiology of the central and peripheral nervous systems. Komatsu et al. in the year 2003 showed that the second derivative of the PPG pulse (i.e. the acceleration photoplethysmograph) at the finger had significantly different wave features in migraine sufferers during headache free periods compared to control subject [71].

IV. DESIGN AND DEVELOPMENT OF WIRELESS PPG SYSTEM

Based on the literature review, it is found that there is a need of an accurate and reliable PPG data acquisition system for the present work. The block diagram of such transmittance type PPG system designed and developed is as shown in Fig.3. It consists of light emitting diode (LED, 660nm) acts as source of light, light dependent resistor (LDR) as a photo-detector, an amplifier, filter, ADC and PC. The LED and LDR are mounted in a probe that fits over the tip of the patient's index finger. The light emitted from LED is passed through the finger in which part of light may be absorbed by the tissues and blood, remaining is transmitted to LDR detector. Each time the heart contracts blood is forced to the peripherals which alter the optical density of light transmitted through the finger accordingly the voltage in the output circuit varies due to change in the LDR resistance [72], [2], [3]. The detected signal is amplified using preamplifier and amplifier to the desired level. A 2nd order Butterworth low pass filter is used with a cutoff frequency of 8 Hz to remove the high frequency noises present. A high pass filter is used with a cutoff frequency of 0.25 Hz which reduces the size of the dominant DC component and enables the pulsatile AC component to be boosted to a nominal level. A notch filter can be incorporated in the design to remove the 50 Hz power line interference that might be present in the signal. The processed output voltage varies accordingly with the amount of blood in the finger and its wave shape closely follows the pressure pulse and is displayed on a digital storage oscilloscope (DSO) [72]. The PPG signal is further digitized, acquired, monitored and stored in a computer system using a dedicated DAS with an in-built ADC through WinDAQ software. The PPG signal acquired may be affected by various artifacts in the patient's environment and can be minimized using Matlab signal processing tool (version 2012b) [73], [74].

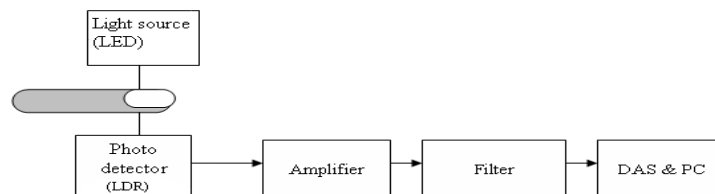


Fig.3 Block diagram of PPG system

In general it is assumed that the amount of light absorbed by soft tissue and skin will remain constant, the only change in the absorption of the light will be due to the increase or decrease of blood volume in the arteries and capillaries. The volume change is an average of all of the arteries and capillaries in the space being measured. The PPG signal is dependent on the tissue and skin type, position of the light source and detector on the body surface, amount of blood volume in arteries and capillaries and the properties of optical devices used [72], [3].

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4.1 Wireless Transmission and Reception of PPG

Developed system is further updated using ZigBee wireless technology for remote monitoring of PPG signals as shown in Fig.4. The transmitter section consists of PPG unit, ARM processor, personal computer and ZigBee wireless module. ZigBee module is of low power consumption and flexible network having 240kbps RF data rate. ARM processor used has inbuilt 10 bit ADC with conversion time of 2.44 μ s. The acquired PPG signal is received by the ARM processor which is interfaced with PC for display and analysis is carried out using Matlab algorithms to find PR, APR, PRV and frequency spectrum. ARM processor sends the PPG data to ZigBee transmitter module for transmission. The transmitted PPG received by the ZigBee receiver to which a PC is interfaced. The physician at the receiver end can access the PPG data and able to and diagnosis of patient health status [75].

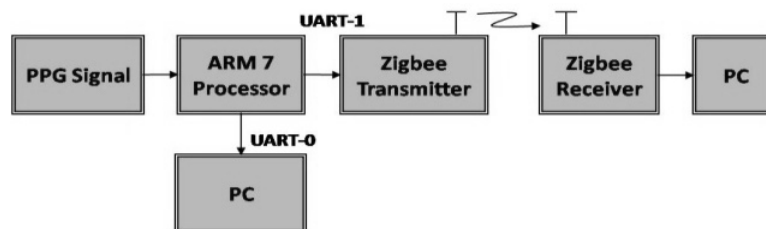


Fig.4 Block diagram of ZigBee based wireless transmitter and receiver for PPG signal

V. RESULTS AND DISCUSSION

The PPG signals are acquired from 15 normal male aged between 25 to 56 years (41 ± 7.1) and 10 normal female subjects aged between 28 to 52 years (40 ± 6.0) and 13 male aged between 52 to 59 and 7 female cardiac patients aged between 49 to 60 years at a sampling rate of 240 samples/ second. The data is collected for different durations of 1, 2, 3, 4 and 5 minutes, in order to assure the reliability and repeatability of the data. PPG signals are analyzed by developing algorithms in Matlab to find the PR, APR, PRV and frequency components.

Fig.5 shows the screenshot of a typical PPG waveform of a normal subject with two phases, the anacrotic phase being the rising edge of the pulse concerned with systole and the catacrotic phase being the falling edge of the pulse concerned with diastole.

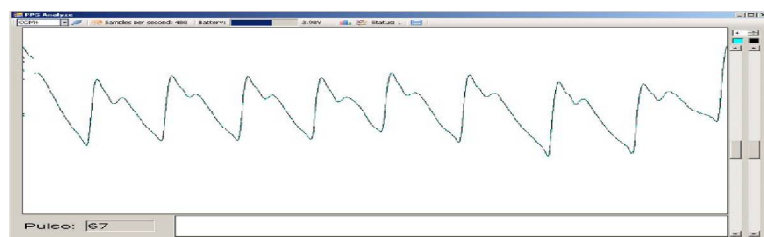


Fig. 5 Screenshot of PPG signal

Fig.6 shows the PPG of 1 min recorded data and PR of a normal subject. The calculated PR value is in good correlation with that of PR measured by standard pulse oximeter. Fig.7 shows the PPG of 3 min recorded data of normal subject and calculated APR which is equivalent to the PR of one minute data.

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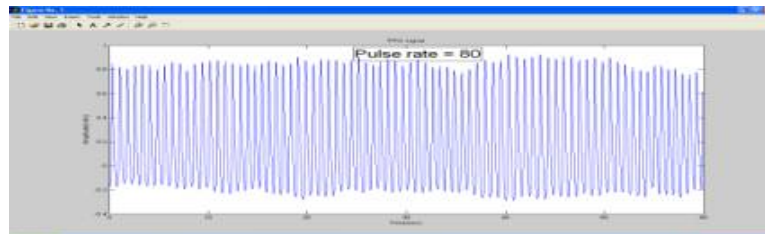


Fig.6 PPG of 1 minute duration with PR of normal subject

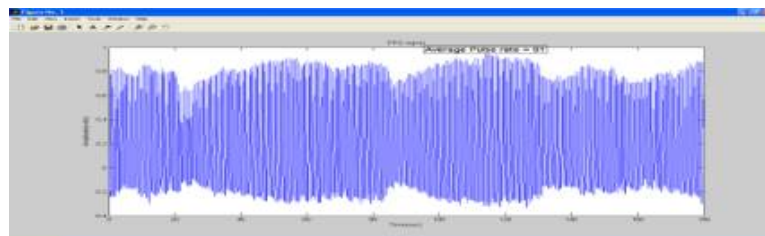


Fig.7 APR for 3 minutes data of normal subject

The instantaneous beat-to-beat changes in the pulse is found by calculating the time duration between the two successive pulses for the entire duration of recording and is plotted as PRV for the normal subject as shown in Fig. 10. The PRV is an indicator of heart rhythm.

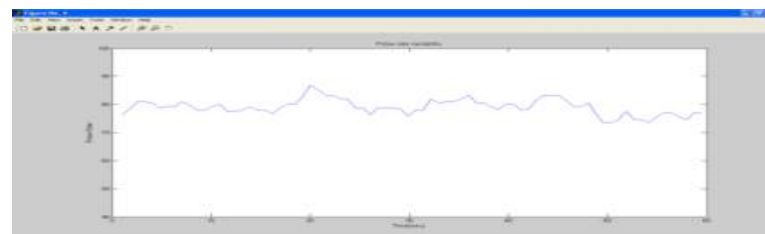


Fig.8 PRV of normal subject for 1 minute data

The Fig. 9 shows the spectrum of PPG pulses of 1 min recorded data for the normal subject. The dominant frequency component occurring at 1.35 Hz indicates good correlation with that of corresponding PR. The very low frequency components and high frequency components contained in a signal are sometimes an artifact caused either by the instruments used to acquire the signal or the movement of the subject and the external light interference, which shifts the PPG signal up or down. These frequency components spread the power spectrum of the PPG signal and can affect the results. Furthermore, the PPG signal consists of a quasi DC signal that corresponds to changes in the venous pressure. This quasi DC signal may be processed to study the respiratory system.

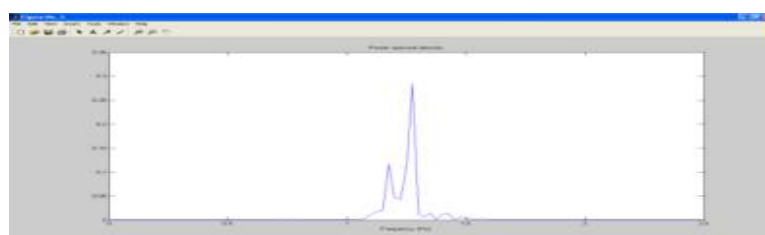


Fig.9 Power spectrum of normal subject

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VI. CONCLUSIONS

This review paper has introduced the technique of Photoplethysmography and has demonstrated its great potential for use in a wide range of clinical measurements. The main focus has been the assessment of the cardiovascular system. There has been a demand for non invasive, low cost, simple and portable system for the primary care and community based clinical settings. Such system can be developed easily with the availability of low cost and small size semiconductor components, and the advancement of computer-based pulse wave analysis techniques. PPG-based technology can be found in a wide range of commercially available medical devices for measuring oxygen saturation, blood pressure and cardiac output, assessing autonomic function and also detecting peripheral vascular disease, despite the characteristics of the PPG waveform not being fully understood. Challenges remain with the technology, including the standardization of measurements, improving repeatability, and establishing comprehensive normative data ranges for comparison with patients and for evaluating responses to therapy. The analysis is carried out in the present work on the recorded PPG data of different subjects for different durations are found to be accurate and are in good correlation with standard methods. The study and analysis shows that PPG can be an alternative diagnostic tool to monitor and study the cardiovascular system.

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