USE OF PHOTOPLETHYSMOGRAPHY IN HEALTH MONITORING.

Measurement and Instrumentation Complex Engineering Problem

Submitted to

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PIEAS

Table of Contents

Abstract:

This report is part of a Complex Engineering problem of Measurement and Instrumentation. In this report, we have discussed various techniques, principles, instrumentation, applications and commercially available devices for photo plethysmographic measurements, clinical use and in daily life. It is a noninvasive, cheap and readily available technology that makes measurements at the surface of the skin. It measures many factors associated with changes in blood flow in human body such as blood oxygen level, blood pressure, stress levels, hypertension, and many other factors. It offers first hand assessments of cardiovascular related diseases. Many modem wearable devices such as wristbands, smart watches and many other devices make use of PPG to monitor to measure these factors during daily routine activities and physical exercise.

1. Use of Photo Plethysmography in Health Monitoring

1.1. Introduction:

1.1.1. Definition:

The word plethysmography means methods for recording volume changes of an organ or a body part. Depending on the technique used, strain gage, impedance, and optical techniques can be used for the volume determination.

Photo plethysmography (PPG) is a simple optical technique used to detect volumetric changes in blood in peripheral circulation. It is a low cost and non-invasive method that makes measurements at the surface of the skin.

Although photo plethysmography is simple and indicates timing of events such as heart rate, it provides a poor measure of changes in volume, and it is very sensitive to motion artifact.

1.1.2. Principle of operation for PPG

The light interaction with tissue processes is complex in most optical physiological measurements. The basic principle of PPG is as follows: to the eye, the human body appears opaque to light transmission. However, most soft body tissues will transmit optical radiation in the visible and near-infrared wavelengths. For example, if visible light, such as a torch beam, is placed on the palm of the hand in a darkened room, the transmitted light can be seen on the back of the hand as a red glow. The transmitted light is colored red because of the selective absorption by tissue pigments, and specifically by hemoglobin in the red blood cells. A halo of back-scattered light around the torch can also be seen. The volume of the red blood cells changes in synchrony with each heart beat and results in small but significant changes in the light transmitted and back-scattered. This pulsatile component is quite small relative to the average transmitted light and is not easily seen with the naked eye. Instead, it can be picked up by an optical detector placed on the skin on the back of the hand. PPG is based on the detection of these small changes in the altered light, which occur with each pulse. The greater the changes in blood in the sample volume, the greater the light source is attenuated. The fundamental frequency of pulsatile (AC) component is usually close to 1 Hz, depending on the heart rate, and is superimposed on a quasi-DC component which relates to the average blood volume in the tissue. DC varies slowly due to respiration, vasomotor activity, blood pressure and thermoregulation. AC and DC components can be measured and separated using electronic amplification and filtering stages.

1.1.3. Techniques:

The principle on which photoelectric plethysmography is based is simple. A beam of light is directed towards the part of the tissue in which blood flow (or volume) is going to be measured (Figure 1). Reflected, transmitted, and scattered light leaving this volume is collected, and focused on a photodetector. A signal modulated by the attenuation or scattering of light in the blood volume can be recorded. Two different components can be derived from the detector. One is pulsatile and synchronous with the heartbeat (the ac component), and the other is a constant voltage (the dc component).

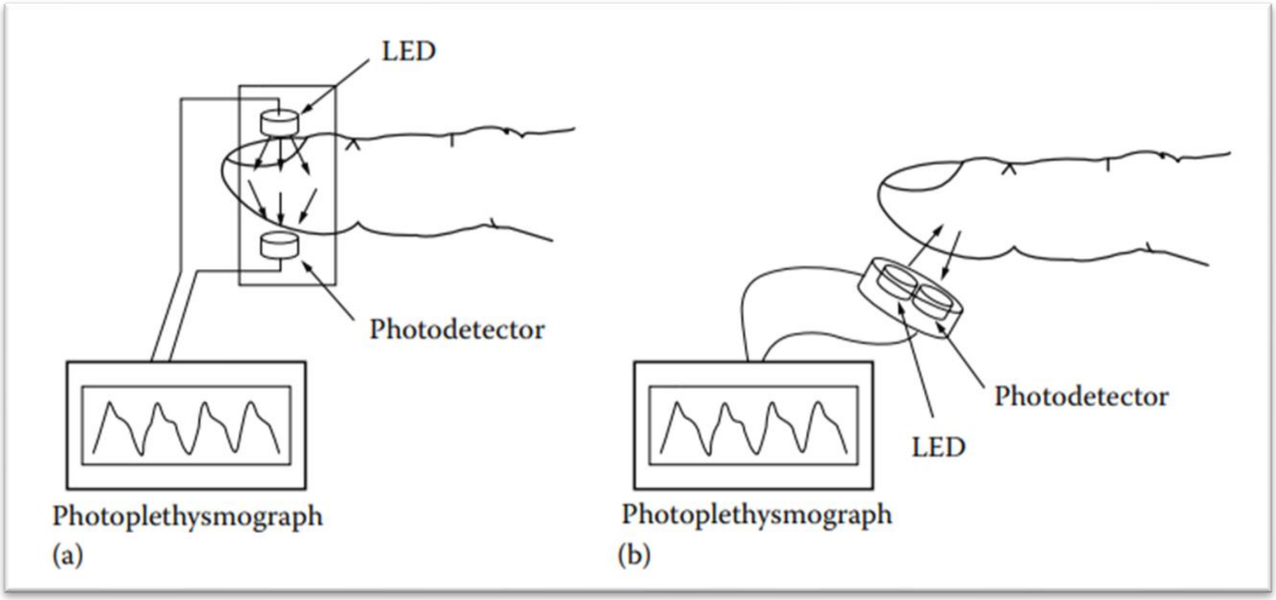


Figure 1: For photo plethysmography, increased blood decreases received light in (a) transmission mode and (b) reflection mode.

Reflection mode PPG is often the mode of choice in vascular assessments since it allows easy attachment to many peripheral sites including the ear lobes, and finger/toe tissue pads. Here, movement and ambient light artefacts can be reduced by suitable fixation, such as with a (black) Velcro wrap-around cuff (e.g. for the finger and toe sites) or covered spring-loaded clip (e.g. for the ear site).

1.2. Photo Plethysmograph:

Photo plethysmograph shows the blood flow changes as a waveform with the help of a bar or a graph as shown in figure (2). The waveform has an alternating current (AC) component and a direct current (DC) component.

The AC component corresponds to variations in blood volume in synchronization with the heart beat. The DC component arises from the optical signals reflected or transmitted by the tissues and is determined by the tissue structure as well as venous and arterial blood volumes.

The DC component shows minor changes with respiration. The basic frequency of the AC component varies with the heart rate and is superimposed on the DC baseline.

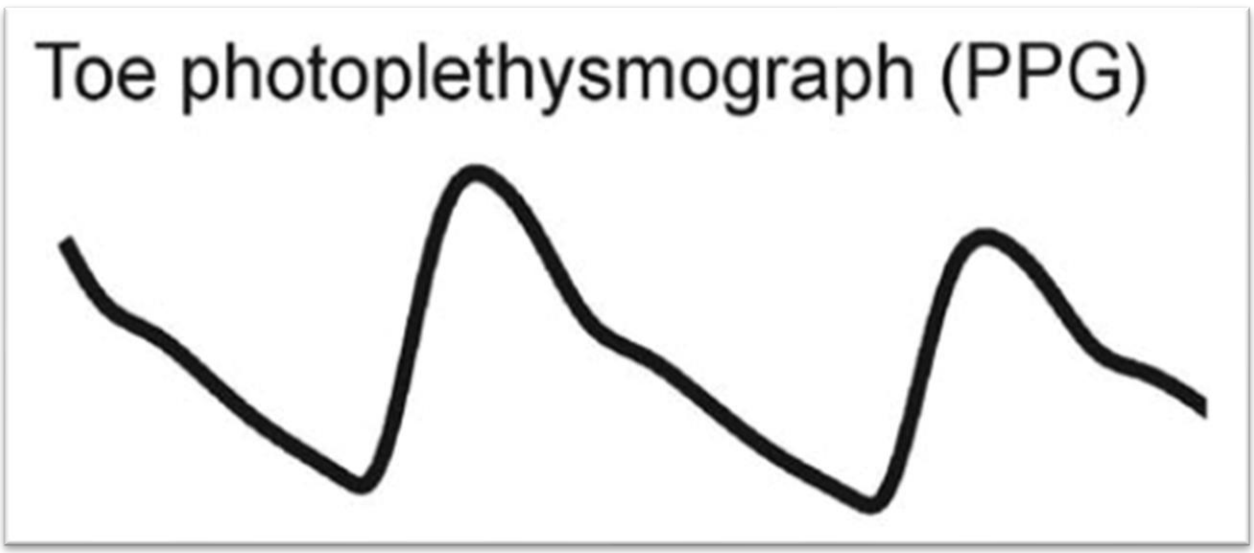


Figure 2: Photo plethysmography AC waveform from the toe site of a healthy subject over a few seconds. PPG detects the pulsatile changes in blood volume in the tissue vascular bed with each heartbeat.

1.3. Optical instrumentation:

1.3.1. PPG transducer:

A semiconductor light emitting diode (LED) is often used with the LED wavelength fixed within the near infrared range 0.8 to 1.0 µm. LEDs have considerable advantages; they have a narrow bandwidth, are small and low-cost, mechanically robust, and have a long operating life. The intensity of the LED is often chosen to be small to reduce local tissue heating.

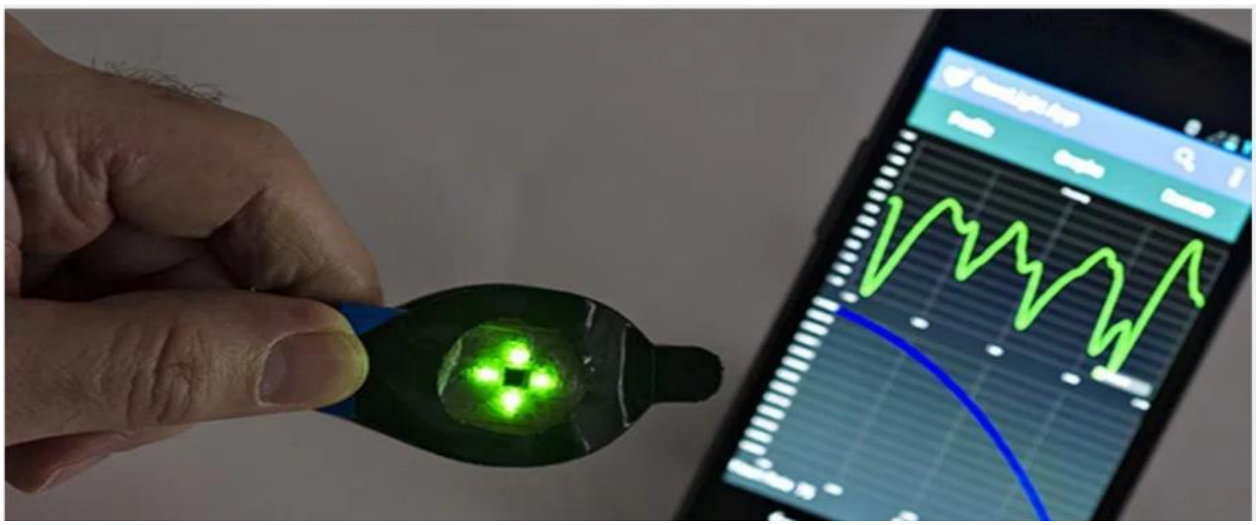


Figure 3: PPG transducer connected to mobile phone for viewing photo plethysgraph.

1.3.2. Photodiode:

The optical radiation back scattered from the tissue, can be detected with a photodiode matched to the LED wavelength. Photodiodes have the capability for producing an output linearly proportional to the incident light, are compact and low-cost, have fast response times, and are sensitive. The LED and photodiode are packaged either side-by-side (“reflection mode”) or can be placed on the opposite side of the tissue (“transmission mode”).

1.3.3. PPG probes:

There are several types of PPG probes that are commercially available. For example, Artema (Denmark) range of pulse pick-up probes (ear probe type 75331-9, and toe/finger probe type 75333-5). Their operating wavelength is 950 nm using constant low-level tissue illumination (with output power less than 5 mW).

Figure 4: A typical PPG probe

1.3.4. PPG amplifier:

The generic structure for a PPG amplifier involves a trans-impedance amplifier stage to convert the photodiode current signal to a proportional voltage. The simplest form of trans-impedance amplifier requires only an operational amplifier with feedback and offset resistors. The choice and layout of these components are crucial to obtain low-noise pulse waveforms. Meticulous cable-screening is also needed to reduce contamination by electromagnetic interference. The voltage signal is high-pass filtered to reduce the dominant lower frequency (DC) PPG components, leaving the AC pulsatile component for further processing. A low-pass filtering stage with additional electrical mains frequency notch filtering then smoothens the signals. The choice of high-pass filter cut-off frequency is important for PPG measurements, as excessive filtering will distort the pulse shape. Typically, the PPG filter bandwidth is chosen to be in the range 0.05 to 20 Hz.

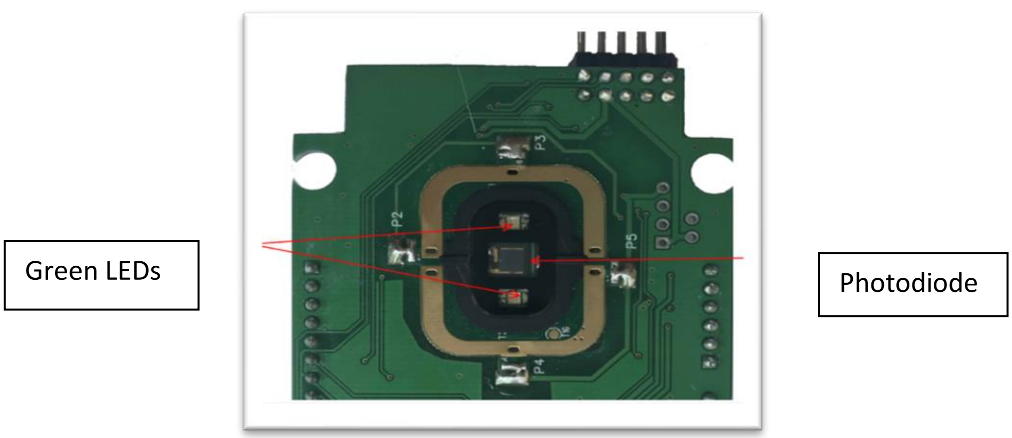


Figure 5: Integrated Circuit module for photo plethysmography

1.3.5. Constant LED current source:

A constant-current generator source can be used for the transducer LED illumination. The electronic design should aim to minimize the noise on the LED signal, and tight current control is required when studying the low frequency (DC) components of the PPG waveform over periods of several tens of minutes.

Figure 6: Wristband type PPG equipment.

1.3.6. Circuit for Solid State photo plethysmograph:

Figure (7) shows the complete circuit for Solid State photo plethysmograph.

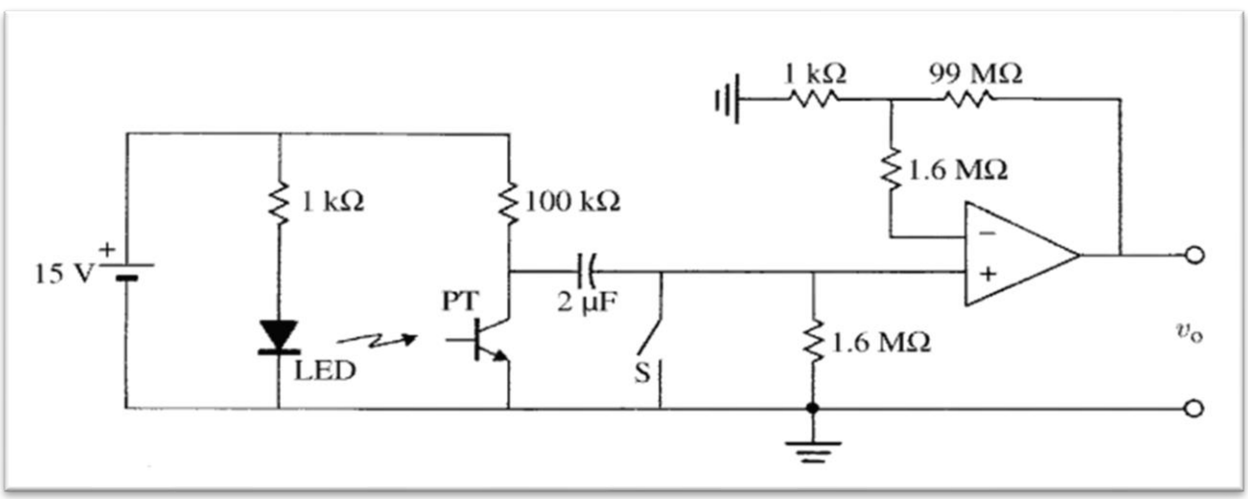


Figure 7: In this photo plethysmograph, the output of a light emitting diode is altered by tissue absorption to modulate the phototransistor (PT). The DC level is blocked by the capacitor, and switch S restores the trace.

1.4. PPG measurements:

Photo plethysmography is undertaken in a clinical measurement environment (ideally normo-thermic at approximately 23ºC). The subject should be rested for a period of at least 10 minutes before pulse measurements commence. The PPG transducers are then carefully applied. The subject is asked to relax and breathe gently and regularly throughout the recording. A PPG recording typically lasts a few minutes when assessing just the AC characteristics of the pulse and several tens of minutes when assessing the DC characteristics.

1.5. Multi-channel PPG capability:

There are advantages in studying several body sites simultaneously to give representative information about the whole cardiovascular system. This can be achieved using multi-channel channel photo plethysmography, see figure (8).

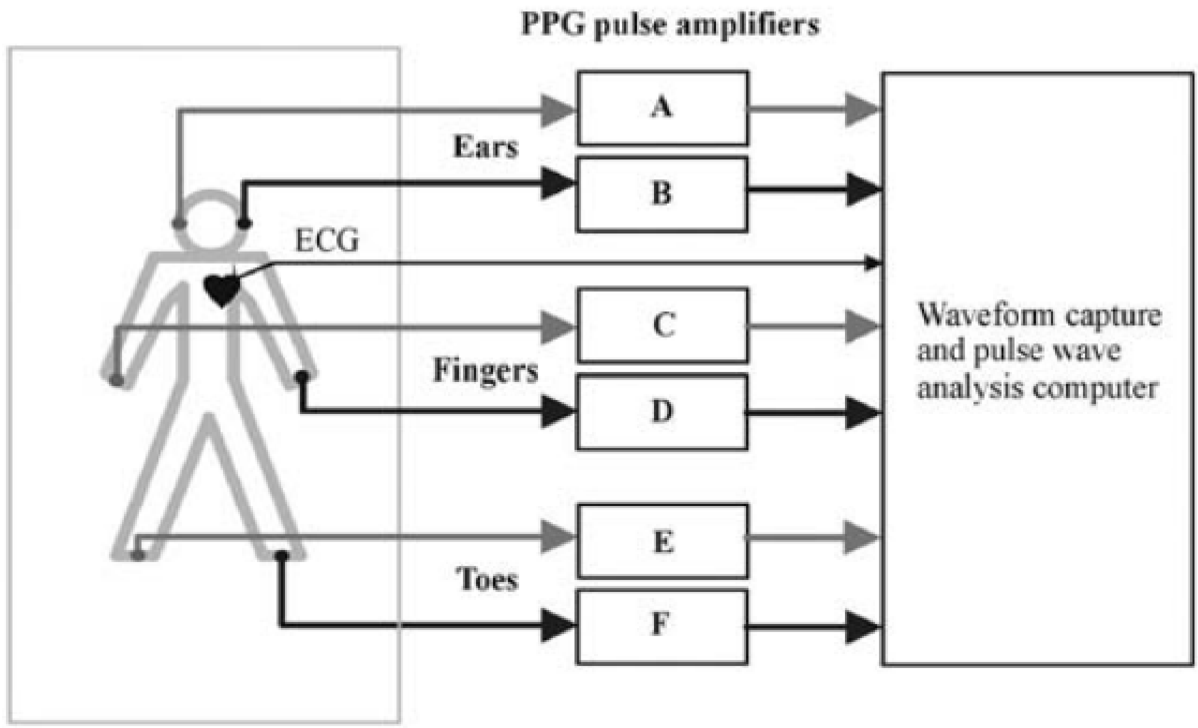


Figure 8: Multi-channel photo plethysmography. In this example, pulses are collected from PPG pulse transducers at different body sites and signal conditioned using the PPG amplifier units (A to F).

1.6. Pulse Transit Time:

Pulse transit time (PTT) is commonly determined as the time difference between onset of cardiac ejection (approximated by the R peak in the electrocardiogram (ECG)) and the arrival of the pulse to the measurement site as determined from the photo-plethysmograph. This is illustrated graphically in figure (9).

The main difference between heart rate and pulse rate is the duration the pulse wave takes to complete the distance from the heart to the measurement site. This time is named the pulse transit time (PTT). It is determined as the time lag between the peak of the R-wave on the ECG and the peak value of the corresponding pulse at the measurement site, measured by PPG.

Increases in PTT are related to changes in the cardiovascular system such as lower systolic blood pressure, lower arterial stiffness or an increased pathway length. PTT might be used, amongst others, to detect sleep disordered breathing [8] or as a surrogate measure of blood pressure due to the correlation of PTT with blood pressure. Another promising application of PTT is monitoring of closure of the ductus arteriosus in a neonatal setting [9].

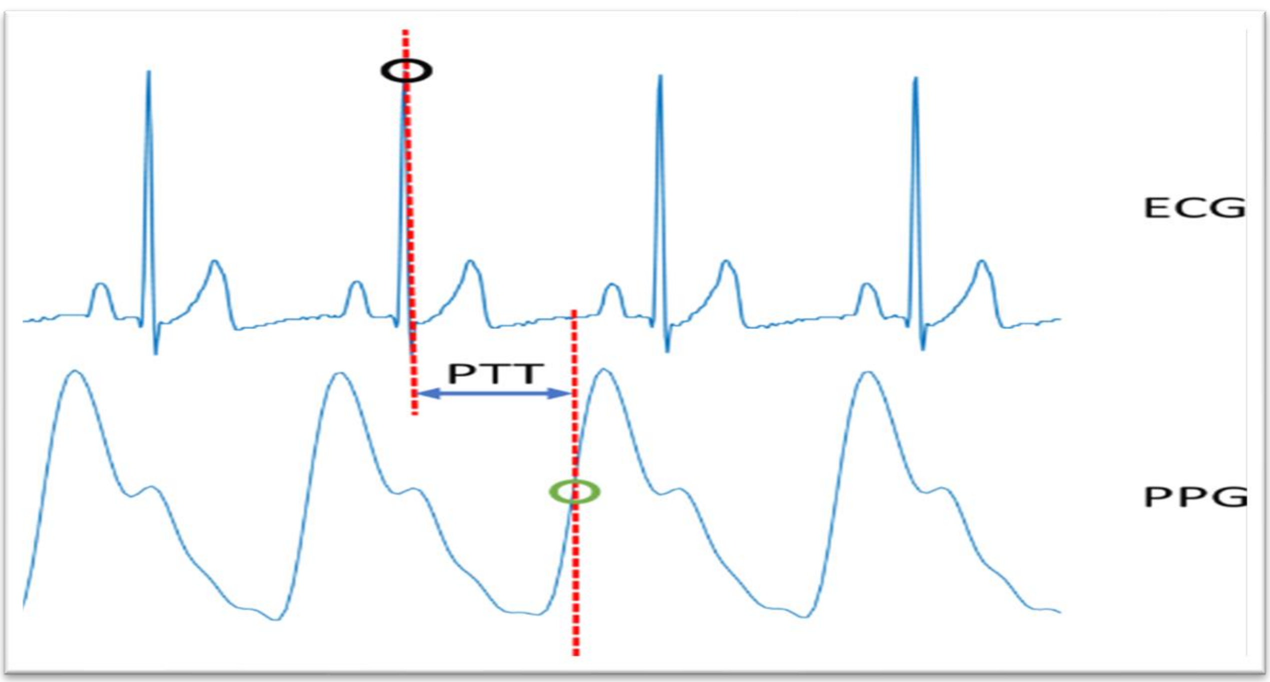
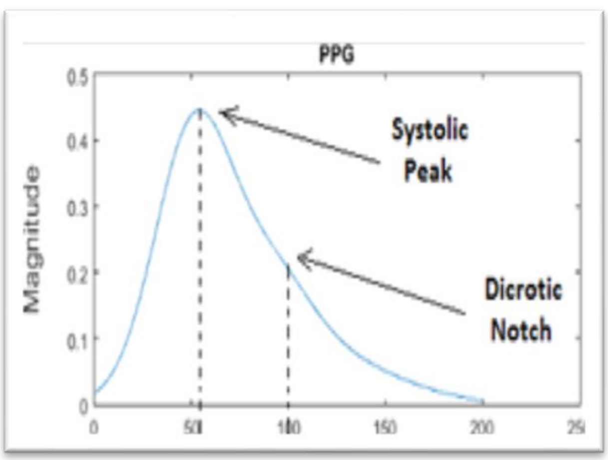


Figure 9: Illustration of pulse transit time calculation. It is depicted as the time difference between the R peak in the ECG (black circle) and the point of 50% increase in the PPG signal (green circle).

1.7. Second derivative wave of PPG signal:

The second derivative wave of the original PPG signal is called the acceleration photo plethysmogram (APG), and it is more commonly used than the first derivative wave. APG is an indicator of the acceleration of the blood. Figure (10) shows the original PPG signal along with its first and second derivative waves. There are several critical points that can be extracted from the second derivative wave of a PPG signal. These critical points can be used to detect and diagnose cardiac abnormalities. Figure (10) shows only three critical points that were extracted from the original PPG signal. Critical point a is the early systolic location. Point b is the lowest point in the early systolic wave. Point c is the resurgent of late systolic. Point d indicates the decreasing part of late systolic and point e represents the early diastolic wave. From the second derivative, we can compute the large artery stiffness index. The APG correlates with age, blood pressure, risk of coronary heart disease, and the presence of the atherosclerotic disorders. The positive waves, namely the a, c, and e waves, rest above the baseline and have positive values, while b and d are negative waves. Thus, the latter waves lie below the baseline due to their negative values. The relationship between the waves represents different physiological trends found in subjects. For example, the ratio b/a represents increased arterial stiffness that increases with age. This ratio can also indicate hypertension. Potential work includes examining the relationship between a/b and studying the impact of age, body mass index, and core temperature on PPG waves. There are algorithms that can detect a-waves and b-waves, but not accurately.



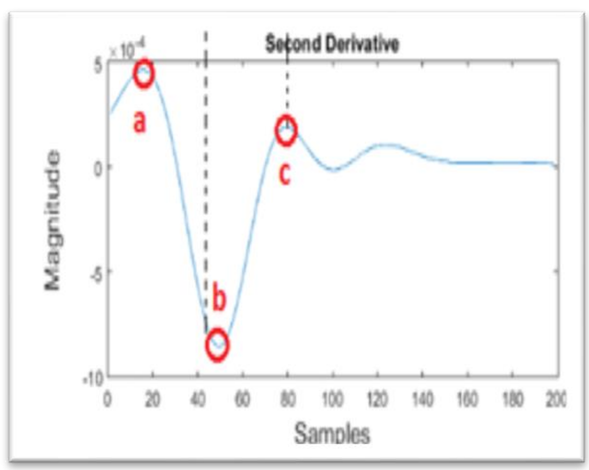


Figure 10: Figure on the left shows photo plethysmograph while that on the right shows its second derivative and the critical points.

1.8. Applications:

1.8.1. Photo Plethysmography assessments in cardiovascular disease:

The circulating medium, blood, is essential for life and provides nutrients such as oxygen and glucose to the muscles, and removes waste by-products. Impairment of this finely regulated system can result in peripheral vascular disease (PVD).

It would probably not be cost-effective for doctors to screen every patient presenting with symptoms of vascular disease. Ideally, what is needed is an initial vascular screening assessment, which accurately determines if a patient has normal arteries or if they should be referred to a specialist for a thorough cardiovascular assessment [3]. The simple, non-invasive, and low-cost optical physiological measurement technique, photo plethysmography has the potential to screen peripheral vascular diseases such as:

- Claudication which is pain caused by too little blood flow to muscles during exercise. Claudication is technically a symptom of disease, most often peripheral artery disease, a narrowing of arteries in the limbs that restricts blood flow.

- Ischemia or ischaemia in which there is a restriction in blood supply to tissues, causing a shortage of oxygen that is needed for cellular metabolism (to keep tissue alive). Ischemia is generally caused by problems with blood vessels, with resultant damage to or dysfunction of tissue.

- Gangrene which refers to the death of body tissue due to either a lack of blood flow or a serious bacterial infection. Gangrene commonly affects the extremities, including your toes, fingers and limbs, but it can also occur in your muscles and internal organs.

Treatments focus on lowering the risks of vascular disease, reducing pain, increasing mobility and preventing damage to tissues. Peripheral artery disease is a sign of poor cardiovascular health and an increased risk of heart attack and stroke.

1.8.2. Heart Rate Measurement:

For a patient who remain quite, the photo plethysmography can measure heart rate. It offers an advantage that it responds to the pumping action of the heart and not to the ECG. When properly shielded, it is unaffected by the use of electro surgery, which usually disables the ECG. However, when the patient is in a state of shock, vasoconstriction causes peripheral flow to be greatly reduced and the resulting small output may make the device unusable. To prevent this problem, the device has been used to transmit light through the nasal septum.

1.8.3. Blood Vessels Assesment:

PPG has great potential to assess the age-related changes in arterial stiffness, an accepted cardiovascular risk factor. It can provide information about the cardiovascular system, such as heart rate or pulsatile pressure, and hence properties of blood vessels, including arterial elasticity, narrowing or occlusion [6]. The pulse is frequently used by clinicians in the assessment of vascular diseases, where a weak, delayed or damped pulse is often a sign of occlusive arterial disease.

1.8.4. Uses of PPG:

Medical devices based on PPG technology are widely used in various applications in the clinical set up. Specific applications include the following:

- Clinical physiological monitoring
- Blood oxygen saturation
- Blood pressure
- Heart rate
- Respiration
- Vascular assessment
- Arterial disease
- Arterial compliance and ageing
- Venous assessment
- Autonomic function monitoring
- Vasomotor function and thermoregulation
- Blood pressure and heart rate variability
- Orthostasis

1.9. Wearable Devices:

Using photo plethysmography, wearable pulse rate monitors such as wristwatch-style fitness trackers with a built-in optical heart rate monitor (see figure 11), have been developed. These low-cost and small devices have high-intensity green light-emitting diodes (LEDs) and photodetectors that help reliable monitoring of the pulse rate in a non-invasive manner. Important design requirements for these systems include miniaturization, robustness and user-friendliness.

Figure11: A multi-purpose smart watch for cardio-vascular assessments.

1.10. Commercially Available Devices:

1.10.1. Pulse Oximeter Fingertip:

There are many pulse oximeters in use these days. These devices were around but they were strongly recognized during the COVID-19 Pandemic as patients with COVID-19 had breathing problems and this device was used to measure their oxygen level in the blood using light absorption in oxygenated and deoxygenated blood. There are many of these devices available in the market or Amazon. One is shown in figure (12) below:

Figure 12: A typical Pulse Oximeter used at fingertip for assessing cardio vascular health.

1.10.2. MightySat® Rx Fingertip Pulse Oximeter:

This product [7] shown in figure (13) can be used for measuring the following parameters:

- **Signal IQ® (SIQ)**: Located under the plethysmographic waveform. The height of the vertical line provides an assessment of the confidence in the SpO2 value displayed.
- **Plethysmographic (Pleth) Waveform:** Real-time graphical representation of changes in volume of arterial blood with each pulse.
- **Perfusion Index (Pi):** A measure of the dynamic changes in the perfusion index (Pi) that occur during the respiratory cycle.
- **Pleth Variability Index (PVi):** The ratio of the pulsatile blood flow to the non-pulsatile blood in peripheral tissue used to measure peripheral perfusion.
- **Respiration Rate from the Pleth (RRp):** A measure of respiration rate based on changes in the plethysmographic waveform. The unit of measure is respiration per minute (RPM).
- It also has optional Bluetooth LE capability and is Compatible with Masimo Professional Health App.

Figure 13: Masimo SET® Measure-through Motion and Low Perfusion™ Pulse Oximetry

1.10.3. The Dash Pro:

The Dash Pro (Bragi, Munich, Germany) is a wireless headset, equipped with sensor technology that is able to provide real-time feedback of recorded movements and pulse rate. The device consists of left and right headphones that communicate wirelessly with each other. The Dash Pro measures pulse rate in the external auditory canal using infrared light by reflection measurement. The device itself is available in one size, but can be fitted to the user's ear with interchangeable silicone caps in sizes XS to L. Figure (14a) shows the Dash Pro with a silicone cap in size M. The blue arrows mark the diodes that allow heart rate detection by reflection measurement. Figure 14b shows the right device, worn in the right ear.

Figure 14: (a) The Dash Pro with silicone cap in size M; blue arrows show the LEDs for pulse rate detection. (b) Right Dash Pro, worn in the right ear.

1.10.4. Cosinuss°One:

The cosinuss° One [10] is a professional fitness tracker monitoring multiple vital signs with stunning accuracy. It has the following features:

- Heart rate
- Body temperature
- 3-D Acceleration

Inside this small and light earplug, the patented ear-connect technology is taking vital sign monitoring to the next level. You can use the cosinuss° One, see figure (15) with all devices featuring Bluetooth or ANT+ .

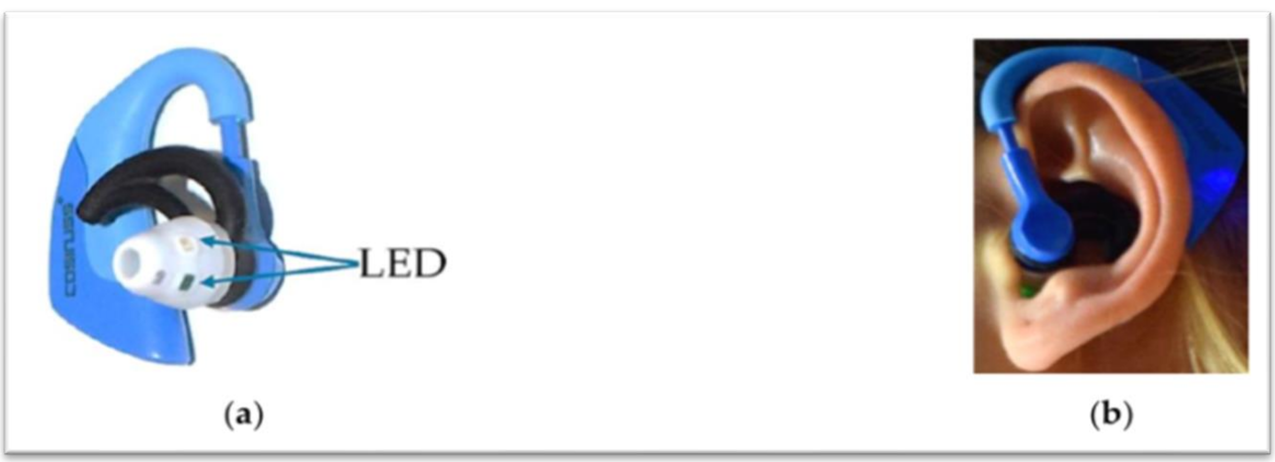


Figure 15: (a) Cosinuss°One; blue arrows show the LEDs for pulse rate detection. (b) Left Cosinuss°One, worn in the left ear.

1.10.5. Probe-Type PPG Sensor:

Probe-type PPG sensors provide real time PPG graph on a laptop or computer.

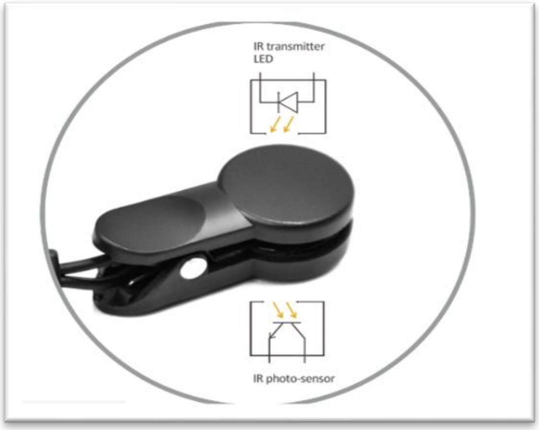


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Figure 16: Finger clips sensor manufactured by Kyto Electronics. Finger pulse sensor HRM-2511B.

1.11. Discussion:

Photo plethysmography (PPG) is a simple optical technique used to detect volumetric changes in blood in peripheral circulation. It is a low cost and non-invasive method that makes measurements at the surface of the skin. It offers first hand assessments of cardiovascular related diseases. Monitoring of heart rate during daily routine activities, physical exercise and monitoring of patients is an important feature in many modem wearable devices such as wristbands and smart watches and many other devices. Obtaining high quality PPG signals during physical exercise is difficult and challenging as PPG signals are usually contaminated by very strong motion artifacts caused by subject’s hand movements. This area of research has been very popular for the past few years and many leading high-tech companies and academics have been actively working on this topic. Currently researchers are investigating the effects of motion artifacts on the quality of acquired PPG signals and proposing solutions to mitigate or ideally remove this destructive affects. Accelerometer is used in some cases to remove the motion artifacts. Scientific interest has continued to look beyond the pulse oximetry and heart rate calculation, and more into the potential applications of PPG sensors. Moreover, the second derivative wave of the original PPG signal contains important health-related information, and the analysis of this wave could lead researchers, clinicians, and health-care providers to the early detection and diagnosis of various cardiovascular diseases typically occurring later in life.

1.12. Conclusion:

The use of photoplethysmography in Health Monitoring has been around for a while in research and commercial use but it has really seen spike in usage during the pandemic. Recently pulse oximeters were in high demand as people with COVID-19 needed them to monitor their blood oxygen levels as they have respiratory problems and they have often got low SpO_2 levels, so they must continuously monitor them. PPG has many applications despite SpO_2 levels, that is, to measure stress, blood pressure, respiratory rate, diagnose cardiovascular disease such as vascular aging and many more. More than 3.8 billion people around the world do not even have basic heath facilities available. PPG sensing is an important technology for the future in health monitoring both remotely and on site and due to its non-invasive nature, convenience and low cost. More and more people around the world can have basic health facilities and can make a better and healthy society.

1.13. References:

1. *J. G. Webster, Ed., Medical Instrumentation. Application and Design, 4th edn., John Wiley & Sons, New York, 2010, pp. 332–338.*
2. *https://journals.sagepub.com/doi/pdf/10.1177/002029400603900303*
3. *AbuRahma, A. F., and Diethrich, E. B., Current Non-Invasive Vascular Diagnosis, Massachusetts: PSG Publishing Company, 1988.*
4. *https://valencell.com/ppgsensors/*
5. *https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6426305/*
6. *Kawarada A, Shimazu H, Yamakoshi K, Kamiya A . Noninvasive automatic measurement of arterial elasticity in human fingers and rabbit forelegs using photoelectric plethysmography Med Biol Eng Comput 1986* ***24****: 591–596*
7. *https://www.masimo.com/products/monitors/spot-check/mightysatrx/*
8. *Chakrabarti B, Emegbo S, Craig S, Duffy N, O'Reilly J. Pulse transit time changes in subjects exhibiting sleep disordered breathing. Respir Med. Elsevier Ltd; 2017;122: 18–22. pmid:27993286*
9. *Amirtharaj CR, Palmeri LC, Gradwohl G, Adar Y, Nitzan M, Gruber D, et al. Photoplethysmographic assessment of pulse transit time correlates with echocardiographic measurement of stroke volume in preterm infants with patent ductus arteriosus. J Perinatol. 2018;38: 1220–1226. pmid:29961764*
10. *https://www.cosinuss.com/en/products/one/*