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Review article

Contact and Non-contact Heart Beat Rate Measurement Techniques: Challenges and Issues

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ABSTRACT

The heart is the most important organ in the human body as it circulates the blood throughout the body through blood vessels. In the human circulatory system, the heart beats according to the body's physical needs. Therefore, the physical condition of a person can be determined by observing the heartbeat rate (HBR). There are plenty of methods that can be used to measure the HBR. Among the methods, photoplethysmography (PPG), electrocardiogram (ECG) and the oscillometric method are the standard methods utilised in medical institutes for continuous measurement of the HBR of a patient. Out of these three methods, PPG is the only method which has evolved to a non-contact imaging-based method from the conventional contact sensory based method. The incentive for developing the non-contact-based imaging PPG method in measuring the HBR provides the advantage of excluding the direct contact of sensors on specific body parts. This brings huge improvements to remote monitoring of healthcare especially for the purpose of social distancing. Moreover, the rapid progression of technology (particularly the interactive electronic gadgets advancement) also motivates researchers and engineers to create a mobile application using the PPG imaging method, which is feasible in measuring the HBR. Hence, this study seeks to review and present the fundamental concept, the present research and the evolution of the aforementioned methods in measuring the HBR.

Keywords: Electrocardiogram, heart beat rate, oscillometric method, photoplethysmography imaging, photoplethysmography

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INTRODUCTION

The heart is the key organ in keeping a person alive. When it stops functioning, the oxygen-rich blood is unable to reach the brain and other organs. A person can die in minutes if the heart stops and does not receive immediate treatment. The HBR is the most direct indicator that can reflect the general health of a person. For instance, the HBR is an indicator for diagnosing any cardiac arrhythmia diseases (abnormal heart rhythms or arrhythmia). This disease is one of the chronic cardiovascular diseases (CVDs). To date, CVDs are termed as the most common diseases causing death worldwide. According to Srinivasan & Schilling (2018), it is estimated that 15 to 20% of all death is caused by CVDs and sudden cardiac death.

Cardiac arrhythmia can be classified into three groups - abnormally fast HBR (or also known as tachycardia, if the HBR is over 100 bpm (beats per minute)), abnormally slow HBR (or also known as bradycardia, when HBR is lesser than 60 bpm) and irregular HBR (Kastor, 2002). A crucial preliminary action in discovering the presence of these diseases is to measure the HBR consistently and frequently. In order to extend the lifespan of a patient who has cardiac arrhythmia diseases, the most effective solution is to attentively monitor the HBR and consume medications. Thus, the measurement of the HBR plays an important role in maintaining the health of the heart.

At present, several techniques and devices can be used in measuring the HBR. The most direct method for calculating the HBR is through manual calculation which is done by putting a bare hand on the arterial site in order to sense the pulsation strength or using a stethoscope to listen the sounds of the heartbeats during a specific time period. As technology nowadays is more advanced, the standard methods such as electrocardiography (ECG), photoplethysmography (PPG) and the oscillometric method are implemented in clinical settings to obtain the HBR automatically. These methods have reduced any errors that may have occurred when the HBR is manually taken. In the paper by Khong & Mariappan (2019), the evolution of the PPG methods had been briefly described. This paper represents an extension of that version by Khong & Mariappan (2019); it reviews the pulse rate or the HBR measurement techniques and focuses on its evolution from contact based to non-contact-based methods.

HEART BEAT RATE (HBR)

The HBR is a measurement referring to the speed of heartbeats in one minute with the measurement unit of bpm. It is essential in analysing the normal resting HBR data. The HBR at rest is a snapshot of the heart muscle in pumping the lowest amount of blood that the body needs. During the resting condition, the HBR is normally between 60 bpm to 100 bpm. For active individuals, the HBR can be as low as 40 bpm as their heart muscle is in better condition and does not need to pump frequently to sustain a steady beat. There are numbers of factors such as emotions, medications, hormones, air temperature, fitness level, activity level, body position, body size, age, and gender. that can affect the normal resting HBR. As these factors can greatly influence the HBR, it is always recommended to check the HBR frequently and at different times of the day under full resting conditions. Table 1 shows the normal resting HBR values.

Table 1
The normal resting heart beat rate values

Group	**Heart Beat Rate (bpm)**
Birth	130-160
Infants	110-130
Children (1-7 years old)	80-120
Children (over 18 years old)	80-90
Adults	60-80

The HBR can be measured by taking the pulse rate (PR) at places where the arteries run near to the skin i.e., wrists, side of the neck, inside the elbow, top or inner side of the foot, back of the knee or groin. In fact, the PR and the HBR refer to the same physiological parameters but they are measured at different body positions and using different techniques. In the following section, the evolution of the methods used for measuring the HBR or PR are presented.

THE EVOLUTION OF HBR MEASUREMENT TECHNIQUES

As mentioned in the previous section, the HBR can be directly measured from the heart or through analysing the PR at the arterial sites in the human body. According to Ghasemzadeh & Zafari (2011), the ancient Indian and Chinese health professionals identified certain diseases based on the strength and speed of the beating pulse by placing a hand on the patient's wrist. When it came to 1816, Rene Theophile Hyacinthe Laennec designed the first stethoscope to listen to sounds produced by the heart and lung (Roguin, 2006). This process is known as auscultation and it is an accurate method in determining the HBR (Hashem et al., 2010). At first, Laennec's stethoscope was made from rolled paper cone. Laennec subsequently changed the material and designed to a simple wooden tube. The most significant change in the development of the stethoscope occurred in 1961 when Dr. David Littmann developed a single tube binaural stethoscope made from stainless steel or light weight alloy (3M Health Care, 2002). Recently, the Littmann stethoscope has evolved to an electronic stethoscope (Leng et al., 2015). However, the classical Littmann stethoscope is still widely used. Since the manual way in measuring HBR needs high attentiveness and might lead to a human error, the methods that can automatically measure the HBR are highly encouraged. These methods will be reviewed in the following sub-sections.

Electrocardiogram (ECG)

Back in 1780, studies of the cardiac electricity started when Luigi Galvani observed the contraction of a muscle caused by the electrical stimulation of a nerve (Fleming, 1997). About 50 years later, Carlo Metteucci discovered that the muscle that connected to the heart by nerves tissues contracted synchronous with the beating heart and all muscles have an electrical current of contraction (Katz & Hellerstein, 1982). Later in the year 1856, Rudolph von Koelloker and Heinrich Muller verified Matteucci's findings by placing the nerve of a nerve-muscle preparation on a beating heart and measured it with a mechanical galvanometer (Bowbrick & Borg, 2006). They noticed that the heart muscle contracted with every systole of the heart and it twitched after the end of every systole (Fleming, 1997). They also proved that the heart muscle is able to produce electric activity and these phenomena later become the QRS complex and the T wave in the ECG as shown in Figure 1.

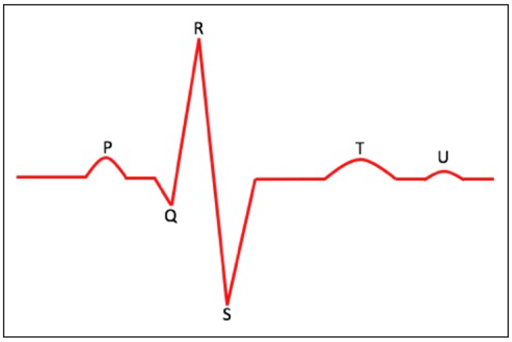


Figure 1. The basic pattern of heart activity obtained from ECG

The next important development of the ECG occurred in 1872 when Gabriel Lippmann introduced the capillary electrometer (Fisch, 2000). This capillary electrometer consists of a glass capillary tube filled with mercury which has contact with sulphuric acid. The surface tension of the mercury altered when there was a potential difference between the acid and mercury. The movements of the mercury are recorded on a photographic paper. Although this method has been used for more than two decades to record any heart electrical activity, it was only applied for the first time on a human heart by Augustus Desire Waller in 1887 (Fleming, 1997). This was also the first time that electrodes were attached on the chest and the back without direct contact to the heart muscle. The subsequent evolutions of these techniques are summarised in first six rows of Table 2.

In 1906, Einthoven developed a standard limb lead system (Lead I, II and III) as the reference positions for the placements of the electrodes. This standard limb lead system forms an equilateral triangle where the heart is located at the centre. The three corners of the equilateral triangle are located at the right arm (RA), left arm (LA) and left leg (LL). Based on the invention of Einthoven, this equilateral triangle is named as Einthoven's triangle. The standard limb lead system is also known as bipolar leads because Lead I measure the bio-potential between RA and LA, Lead II measures the bio-potential between RA and LL, and Lead III measures the bio-potential between LA and LL. In 1924, Einthoven was awarded the Nobel Prize in medicine due to his contribution in inventing the ECG (Yang et al., 2015).

Table 2
The Evolution of ECG Technic

Year	Research(s)	Technics	Remarks
1891	William Bayliss and Edward Starling	Capillary electrometer	Used improved capillary electrometer with a more powerful projecting microscope optics and an additional electrical light to extract 3 different deflections, which later known as P wave, QRS complex and T wave in ECG (Fye, 1994)
1903	Willem Einthoven	String galvanometer	Since frequency response of capillary electrometer is poor, string galvanometer is developed (Madihally, 2010).
1905-1907	Cambridge Instrument Company	Einthoven string galvanometer	Three units Einthoven string galvanometer were successfully manufactured and sold (Fye, 1994)
1909	Edelmann	Small version of the string galvanometer	Set up in Thomas Lewis's laboratory at University College Hospital in London (Fye, 1994)
1909	Alfred Cohn	First Edelmann string galvanometer ECG machine	Introduced to United States and installed at Mt. Sinai Hospital (Geddes & Wald, 2000)
1914	Charles Hindle	First ECG machine	Charles Hindle built the first ECG machine in United States , which was designed by Horatio Williams (Geddes & Wald, 2000)
1934	Frank Norman Wilson	Wilson's central terminal	Wilson's central terminal forms by connecting the electrodes at RA, LA and LL respectively to central terminal. The bio-potentials measured based on Wilson's central terminal are voltage at right arm (VR), voltage at left arm (VL) and voltage at left foot (VF) (Alghatif & Lindsay, 2012).
1938	American Heart Association	Six standard precordial leads	The Cardiac Society of Great Britain and the American Heart Association standardized the name for the six standard precordial leads as V1–V6 (Alghatif & Lindsay, 2012)
1942	Emanuel Goldberger	Augmented leads system	Augmented leads system i.e. augmented vector right (aVR), augmented vector left (aVL) and augmented vector foot can amplify the bio-potentials of VR, VL and VF (Gargiulo, 2015) and replace them in the ECG measurements.
1954	American Heart Association	Twelve leads system	Twelve leads system consists of bipolar leads (Lead I, II, III), augmented leads (aVR, aVL, aVF) and standard precordial leads (V1-V6) has been recommended for standardizing the ECG measurements (Alghatif & Lindsay, 2012).
1957	Normal Holter	Holter ECG	New breakthrough in ECG development. Holter ECG is a portable device and can continuously record the heart activities (HBR and rhythm) for more than 24 hours (Yang et al., 2015).

In 1934, Frank Norman Wilson developed Wilson's central terminal by connecting the electrodes at RA, LA and LL respectively to the central terminal. In Wilson's technique, this central terminal acts as a reference terminal and hence, it is also known as unipolar leads (Alghatrif & Lindsay, 2012). Wilson also based on Wilson's central terminal technique to measure the bio-potential across the chest with six standard precordial leads.

The evolutions about the lead systems are summarised from the seventh to tenth rows of Table 2. Figure 2 shows the Mason-Likar leads position for the ten electrodes to form a twelve-lead ECG system. To date, this twelve-lead ECG system is still applicable to ECG measurements and is also known as the golden standard in measuring the activity of heart in clinical settings including the HBR.

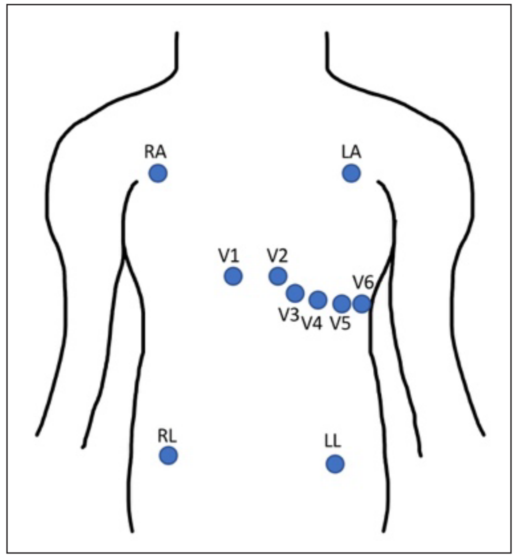


Figure 2. Mason-Likar leads position for the ten electrodes to form a twelve-leads ECG system

Although the twelve-lead system is able to describe heart activities, the ECG machine is bulky and expensive. Throughout the years, the ECG machine greatly advanced in terms of weight by reducing the Einthoven string galvanometers from 600 pounds to less than 8 pounds (Fisch, 2000). In addition, the number of operators needed was reduced from five to one person. The electrodes used in the ECG machine were also improved from Einthoven's original cylinders, which consist of electrolyte solutions to strap-on electrodes designed by Alfred Cohn in 1920 (Krikler, 1983). In 1932, Rudolph Burger introduced a suction electrode which was later improved by Welsh in the ECG machine (Burch & DePasquale, 1990). In order to avoid the pain caused by the suction electrode, an electrode with adhesive gel was introduced. Silver (Ag) or silver chloride (AgCl) electrodes are the most typical and preferred electrodes used in clinical ECG measurements nowadays for the recording of bio signals (Albulbul, 2016).

Holter's ECG is normally used to monitor patients with heart attacks or after surgery, in evaluating the pacemaker functionality or assessing the efficiency of the medicine. During the period of monitoring, the research subjects were prohibited to get wet, have X-rays or use an electric blanket when wearing the device (UW Health, 2016). In addition, the research subjects were also required to keep a distance from high-voltage areas, electromagnetic fields or metal detectors.

As medical technology advanced, Applied Biomedical Systems BV and AliveCor Inc. invented a handheld ECG device called MyDiagnostick and Kardia Mobile respectively (Desteghe et al., 2017). MyDiagnostick is a rod-like device with electrodes at both ends as illustrated in Figure 3 used for ECG recordings and atrial fibrillation detection. The subject is required to hold the electrodes with both hands for one minute. MyDiagnostick has a USB connecter at one end for ECG records to enable the transfer of the readings from the device to a computer. Kardia Mobile is required to connect with a mobile phone that has the Kardia app installed. Kardia Mobile was invented for single channel ECG recordings, atrial fibrillation detection, heart rhythm diagnosis and the HBR measurement (AliveCor Inc., 2017). The subject is required to place two or more fingers of both hands on the electrodes at both sides of the Kardia Mobile for at least thirty seconds. The other product which can be used for measuring the ECG is Apple Watch Series 4, 5 and 6. However, this feature is not yet available for all the countries.

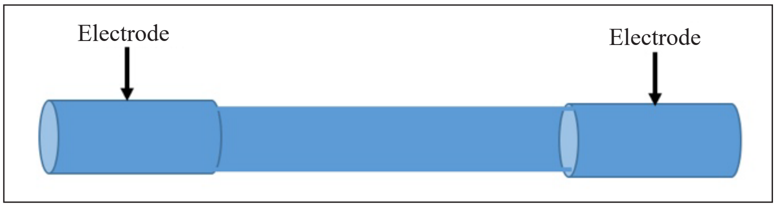


Figure 3. MyDiagnostick designed by Applied Biomedical System BV has electrodes at both end of sides

The ECG is a powerful method for the monitoring of heart activities. Hence, many researchers have built their own circuit for ECG signals extraction. From the peak-to-peak interval of the ECG signals, the HBR can be measured. The main drawback of the ECG is the subject requires contact with the electrodes to obtain the measurements. Therefore, it is very inconvenient.

Oscillometric Method

Oscillometric method is normally used in an automated electronic blood pressure measurement device that consists of inflatable cuff, pressure transducer, circuitry for signals conditioning, analog to digital converter, microcontroller and liquid crystal display (LCD) (Drzewiecki, 2003). Table 3 shows the evolution of the blood pressure measurement

Table 3
The Evolution of Oscillometric Method

Year	Research(s)	Technics	Remarks
1855	Karl von Vierordt	First sphygmograph	Can record the arterial pulsation for blood pressure measurement (Kapse & Patil, 2013).
1860	Etienne Jules Marey	Marey's sphygmograph	Improved the multi-levered and bulky version of Vierordt's sphygmograph and can record the velocity and waveform of the arterial pulsation on a graphical paper by immersing the whole arm inside a glass chamber that filled with water (Kapse & Patil, 2013).
1876	Etienne Jules Marey	Oscillometric method	He observed that the pressure in the cavity was fluctuated when he placed the whole arm inside a pressure cavity and noticed that the pressure fluctuation actually was varied with the amplitude of his pulsation (Geddes, 1991). This amplitude can be used to measure the blood pressure.

techniques. To date, the oscillometric method is still widely used to record the pulsation oscillation but the instrument has been improved by changing the mechanical components to electronic components that can automatically interpret and analyse the pulsation signals.

Although the oscillometric method was mainly developed for the measurement of blood pressure, it can also be used to measure the PR due to the transducer in the inflatable cuff which can sense the oscillation of the pulsation. The oscillometric device normally records the oscillation of the pulsations either by the inflating or deflating of the cuff. The recorded raw pulsation signals are amplified and filtered with a signal conditioning circuitry to separate the pulsation signals. Subsequently, pulsation signals are converted from the analog to digital form. Since the oscillometric device directly measures the arterial pulsation oscillation, the peak-to-peak intervals of the digitized pulsation signals are used for the calculation of the pulse rate (Yamakoshi et al., 2014). The calculated PR is displayed on the LCD.

Typically, three types of automatic oscillometric devices are available in the market i.e., upper arm, wrist, or finger oscillometric device. According to the guideline of the European Society of Hypertension, the upper arm oscillometric device is the most reliable device for the measurement of blood pressure and the PR (Parati et al., 2008) as the brachial artery of upper arm is the main supplier of blood from the arm to the finger. Besides that, the heart is the same level with the upper arm and hence, is able to provide more accurate reading. However, any movement during the pulsation recording causes the results to be rendered inaccurate. Since the automatic oscillometric device is easy to operate, it is widely used for self-health monitoring at home.

Photoplethysmography

Photoplethysmography (PPG) is derived from the word's "photo" and "plethysmography", where photo implies the optical ability and plethysmography represents the measurement of the volumetric changes (Lemay et al., 2014). The PPG measures the HBR by detecting the changes of blood volume within the human cardiovascular system through the application of an optical technique (Allen, 2007). The heart is the core organ and aims to circulate blood throughout the body. Blood contains haemoglobin which is capable of absorbing the radiation of optics. Thus, the variation of blood volume influences the intensity of the remittance spectra as the vascular circuit is illuminated by a light source. By measuring these variations, the timing of cardiovascular events can be examined and it is a valuable information for computing the PR. In view of this relation, the PPG method was developed. The subsequent establishment of contact conventional PPG technique and the recent development of non-contact-based PPG technique are discussed below.

Contact Based Photoplethysmography (PPG)

Pulse oximeter is a typical medical device that applies the PPG method in continuously acquiring the patient's PR in the hospital. Initially, it was innovated to observe the oxygen levels of the human blood. It also has the ability to detect the cardiovascular pulse waves, which propagates via the human microvascular. The PPG signals also conveys PR data that is computed by analysing the PPG either using time domain analysis (time interval between two consequent peaks in the PPG waveform) or frequency domain analysis (PPG spectral analysis by detecting the highest frequency peak) (Zhang, 2015).

With reference to the Beer-Lambert law shown as Equation 1 (Gastel et al., 2016), the principle of pulse oximeter is formed.

$$I = I_0 e^{-\varepsilon(\lambda)cd} \qquad [1]$$

where I_0 implies the utilised light source intensity, ε considers the examined substance's specific molar extinction coefficient, λ represents the particular wavelength, c indicates the examined substance's concentration and d depicts the optical path length. I indicates the intensity of the transmitted light.

In compliance with the Beer-Lambert law, the absorbance of the examined substance is directly proportionate to the specific molar extinction coefficient of the examined substance, the concentration of the examined substance and the optical path length. Thus, the equation for calculating the test substance absorbance can be formed as Equation 2 with rearranging Equation 1. A is the absorbance of test substance.

$$A = ln\frac{I}{I_0} = -\varepsilon(\lambda)cd \qquad [2]$$

According to the definition of the Beer-Lambert law, when the light sources illuminate the clamped finger in the pulse oximeter, the light transmits through the skin of the finger and is absorbed by the entire substance of the finger. The substances of the human finger can be broadly grouped into two categories, which are termed as the pulsatile (AC) component (i.e., arterial blood) and the non-pulsatile (DC) components (i.e., muscle, bone, tissues, and venous blood). The AC component is the only substance that performs and varies with time, as it is influenced by the pulsation. Hence, the AC component is intensely affected by the cardiac cycle and undergoes rhythmic small variations based on the amount of absorbed light. Whilst the light being absorbed by the DC components is almost consistent with time, the change maybe very minute as the concentration of haemoglobin amount varies. Typically, the amount of light absorbed by the DC components is assumed to be same to ease the calculation of the pulse oximeter during the cardiac cycle. For the HBR calculation, the time interval from the peak to peak of the PPG signal is adopted. Figure 4

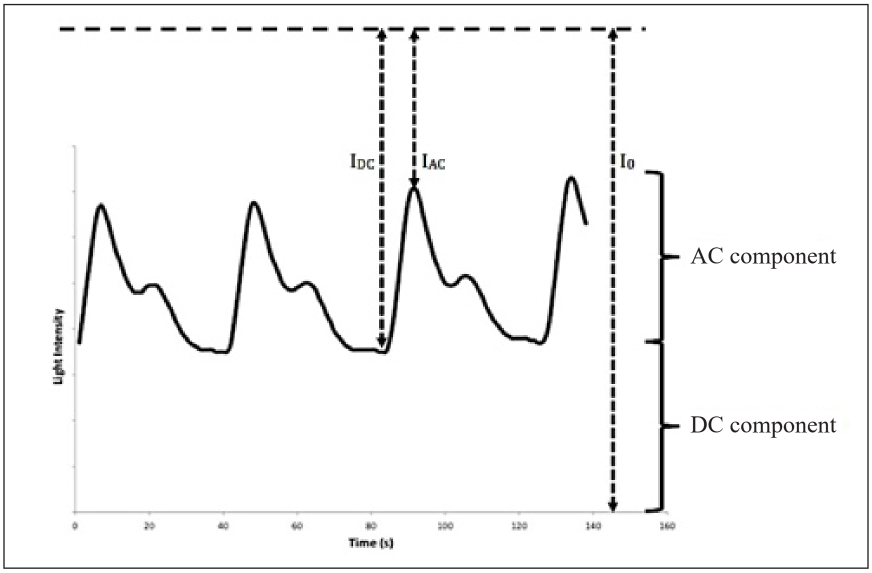
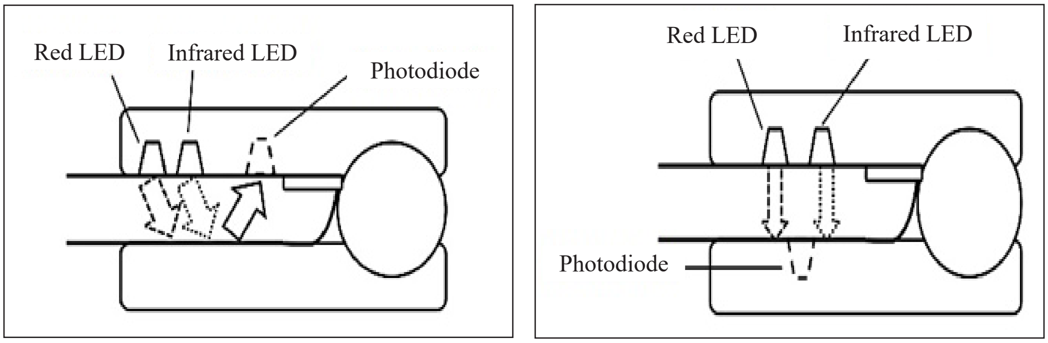


Figure 4. The obtained PPG signal from pulse oximeter with specific wavelength



(a) (b)

Figure 5. (a) Reflectance; and (b) Transmission type of pulse oximeter

describes the PPG signal, which is obtained from pulse oximeter with specific wavelength. It shows that the upper part of the PPG signal represents the AC component, whereas the lower part of the signal implies the DC components.

In most cases, the pulse oximeter comprises of two light sources (infrared light at 840 nm and red light at 660 nm) to illuminate the human body tissue and a photo-detector to detect the light intensities that re-emit from the human tissue. After the light intensities are collected, they are filtered by a band pass filter circuitry. Subsequently, these filtered signals are digitalized and a microprocessor is implemented to process the signals for the cardiac output measurements. Nowadays, there are generally two types of pulse oximeter available in the market; a reflectance type and a transmission type, as shown in Figure 5 (Laurent et al., 2005). For a reflectance type pulse oximeter, the light sources are attached on the body tissue surface and placed adjacent with the photo-detector. Within the transmission type pulse oximeter, the photo-detector and light sources are positioned opposite with the body tissue in between.

The development of PPG started in the early 1936 and its early progress is summarised in first four rows of Table 4. For the next two decades, the bulky, heavy, motion sensitive

Table 4
The Development of PPG Technic

Year	Research (s)	Technics	Remarks
1936	Researchers of Stanford and New Jersey	Non-invasive optical method	Initiated the development of non-invasive optical method to examine the blood volumetric variations in rabbit ears (Lemay et al., 2014)
1937	Alrick Hertzman	PPG technique	Published his first finding on measuring human blood volumetric changes from tissues with PPG technique (Alian & Shelley, 2014)
1939	Karl Matthes and Franz Gross	Red and infrared wavelength in PPG technic	Used red and infrared wavelengths to PPG signals and compared their performances (Laurent et al., 2005). The ear prove was introduced to record PPG signals.
1942	Glen Millikan	Ear oximeter	The word 'oximeter' was officially employed and he introduced the ear oximeter, which is a reduced weight of Matthes and Gross's ear probe (Severinghaus, 2007)
1971	Takuo Aoyagi	Dye dilution method in Ear Oximeter	Takuo Aoyagi from Nikon Kohden Company attempt to use dye dilution method for increasing the accuracy of the ear oximeter in measuring cardiovascular events (Aoyagi, 1992)
1975	Nihon Kohden Company	Ear pulse oximeter OLV-5100	Commercialized the first ear pulse oximeter OLV-5100 with incandescent light, photocells and filters to acquire PPG waveform generated by arterial pulse for determining SpO2 based on Aoyagi's concept (Severinghaus, 2014)
1981, 1983	Biox and Nellcor Inc.	Pulse oximeter Ohmeda Biox 3700 (Ear probe) and Nellcor N-100 (Finger probe)	Developed and commercialized the pulse oximeter Ohmeda Biox 3700 (with flexible ear probe) (Ohmeda, 1986) and Nellcor N-100 (with flexible finger probe) (Mahgoub et al., 2015). They are the initial pulse oximeter adopted red and infrared LEDs (Ohmeda Biox 3700-wavelength 660nm and 940nm; Nellcor N-100-wavelength 670nm and 940nm), a photodiode and a microcomputer for cardiac output measurements.
1990	Nonin Medical Inc.	Hand-held pulse oximeter	Attributed the next evolution of pulse oximeter by manufactured a portable hand-held pulse oximeter model 8500 (Nonin Medical Inc.,2014).
1991	Nonin Medical Inc.	Fiber Optic sensor	Innovated the pulse oximeter with the fiber optic sensor (Nonin Medical Inc.,2014).
1992	Takuo Aoyagi	Dye of Indocyanine Green (ICG)	Used for cardiac output measurement because ICG has been approved by Food and Drug Administration (FDA) in 1959 for medical diagnostics due to its low toxicity to human health (Sinagra & Dip, 2015).
1995, 2004	Nonin Medical Inc.	Fingertip pulse oximeter	Invented the fingertip pulse oximeter Onyx Model 9500 and Onyx II Model 9550 with Bluetooth and wireless technology correspondingly (Nonin Medical Inc., 2014)

galvanometer and light source used in the ear oximeter still had a limited usage in the medical field. Until 1962, the advancements in semiconductor technology i.e., photodiode, phototransistor and light emitting diode (LED) contributed greatly in reducing the size, increasing the sensitivity and reliability of the oximeter for the PPG measurements (Lemay et al., 2014). According to Aoyagi (1992), the optical density for blood with ICG is determined at wavelength of 805 nm while the blood optical density for blood can only be measured at wavelength of 900 nm. Based on the calculation of the ratio of these two wavelengths, the cardiac output, which is the amount of blood pumped by the heart in a minute is measured. The subsequent evolutions of PPG are summarised in Table 4.

Compared to the finger, the forehead is nearer to the heart and thus, the cardiac output responses are closer relative to the heart rhythms. In addition, the vascular bed in the forehead has blood which is supplied by the supraorbital artery, whereas the finger only involves a capillary bed (Man-Son-Hing, 1968). Therefore, it is validated that the forehead is one of the most apt locations for measuring human physiological parameters.

Due to the rapid growth of the photonic technology, the advancement of the PPG technique is established. Currently, several manufacturers have invented wrist-worn devices to measure the HBR. Shcherbina et al. (2017) had studied and evaluated the accuracies of seven commercial wrist-worn devices, which include the Apple Watch, Samsung Gear S2, Microsoft Band, Fitbit Surge, PulseOn, Basis Peak and Mio Alpha 2. According to the findings, the Apple Watch accomplished the highest accuracy for the measurement of the PR. The Apple Watch is the first product launched by Apple Inc. in year 2014 which is competent in measuring the PR using the PPG signals. To date, Apple has launched up to series 6 of the Apple Watch which is now not only capable in measuring both the PR and the ECG but also the blood oxygen level. However, the measurement of ECG and blood oxygen levels is only available in certain countries. The first Apple Watch series 4 which is able to measure the PR and ECG is shown in Figure 6. In general, the Apple Watch

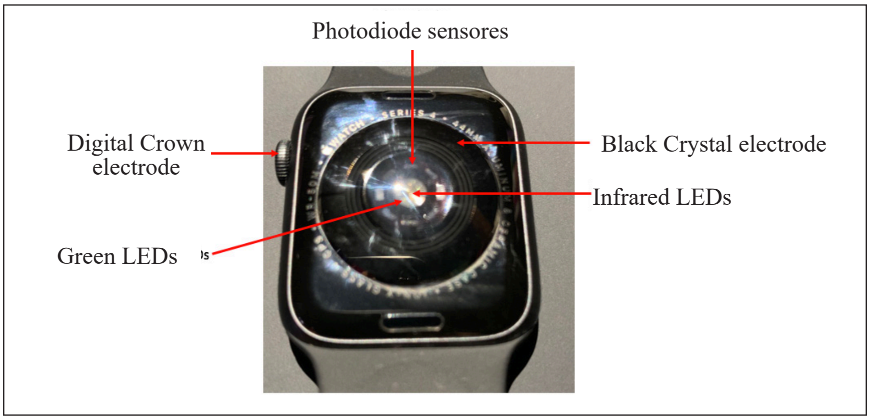


Figure 6. Apple Watch adopts green LEDs or Infrared LEDs and photodiode for PR measurement and Back crystal electrode and digital crown elecrtrode for ECG measurement

utilizes green and infrared lights paired with photodiodes to collect the light intensities for measuring the volume changes of blood around the wrist (Apple Inc., 2020). The infrared light is only applicable for measuring the PR in the background. As the infrared light is insufficient, green light is used for enhancing the light source. Moreover, the brightness of the lights is auto-adjustable based on the detected signal levels.

As a concluding summary from the reviews, the PPG is certified as one of the most outstanding methods to measure the PR and numerous devices have been invented using this technology. Even though the PPG technique is widely implemented for a clinical setting to measure and monitor the physiological parameters, the sensors of the devices i.e., photo sensors and light sources are required to be directly attached on the human skin. This contact basis of the PPG device has created inconvenience for the patients, particularly those with skin problems. In comparison, the recently developed non-contact PPG technology is highly potent for resolving these inconveniences.

Photoplethysmography (PPG) Imaging

With references to the fundamental theory of PPG, engineers and researchers found that the pigmentation of the human skin is feasible in interacting with light. The high advancements of video and video imaging techniques have facilitated the exploration of the video imaging usages by researchers within the health care industries. Video sensors was adopted to replace the photodiode in acting as a photo-detector in collecting the remittance spectra of the skin with both contact and non-contact theory in early 2000s. Its performance in measuring the PR was very promising.

The technology of non-contact PPG imaging had crucially progressed in 2010 when Poh et al. (2010) initiated the utilisation of the built-in webcam in the MacBook Pro for measuring the PR of 12 participants by recording their video images. Investigations were conducted indoor with varying amount of sunlight as the light source. In order to remotely capture the subjects' face for analysis, the webcam was located 0.5 m away from the subjects. The duration of the video recording process was 60 seconds at the rate of 15 fps. In processing, the video signals were processed using 30 seconds moving window with 1 second interval increment. This was the first study which pioneered the blind source separation (BSS) method to reduce the motion artefact from the video signals before it is ready to measure the PR. The BSS method from the Independent Component Analysis (ICA) was implemented by Poh et al. (2010). The ICA aims to separate the signal source mixture into independent components. Once the signals are separated, the power spectrum of the independent component that has the highest Signal to Noise Ratio (SNR) was utilised for computing the HBR while the frequency of the highest peak within 0.75 – 4 Hz was adopted for the PR measurement. The results indicated that the algorithm with the BSS method had higher accuracy than the algorithm without BSS method.

According to Poh et al. (2010), despite used the ICA to reduce the motion artefacts, the pulse frequency computation may occasionally be affected by noise. In order to solve this issue, researchers utilize the past estimations of the pulse frequency by setting a threshold of 12 bpm. If the difference between the current PR estimation and the previous computed PR exceeds the threshold, the algorithm rejects the frequency corresponding to the highest power by searching for the next frequency with the highest power until the threshold is met. If there are no frequencies that meet the threshold, the algorithm remains at the current pulse frequency estimation. Since this method is based on the previous history of PR estimation, once the estimated PR has a false value, it might possibly lead to inaccurate results.

Based on the literature review, the motion artefacts are found as the critical issue for acquiring the HBR out of the non-contact-based PPG imaging signals. Hence, the ICA is still extensively implemented presently for selecting the most noticeable PPG signal in measuring the HBR. According to van der Kooji & Naber (2019), researchers still utilised the ICA for extracting the best signal component of the filtered RGB colour channels to extract the HBR. While the ICA is the well-known approach for the HBR extraction of remote PPG signals, Macwan et al. (2018) enhanced the conventional ICA formulation by augmenting the ICA algorithm using chrominance-based constraints and autocorrelation to a flexible and systematic manner. Macwan et al. (2018) noticed that the enhanced ICA algorithm is feasible in obtaining the most periodic component, which represents the blood volume pulse. Therefore, the obtained signal is consistently nearer to those of the PPG signal which is significant for evaluating the HBR.

Khong et al. (2016) is another study used the built-in 720p FaceTime HD Camera on a MacBook Pro to record video images for PR analysis. Khong et al. (2016) recorded the video in RGB colour mode at the frame rate of 30 fps with pixel resolution of 845 x 480 pixels. The duration of the video images was 1 minute with participants who were seated approximately 0.5 metres in front of the camera. For the light sources, the natural light and fluorescent light were selected to illuminate the participants for the PR measurement. In the study of Khong et al. (2016), only green coloured channels of the video signals were used for the PR extraction and the region of interest was the forehead of the participants. For the video pre-processing step, the researchers normalized the video signals and filtered the video signals with the cut-off frequencies of 0.7 to 4 Hz. This range of frequency was selected because it is the range of PR for a normal person. Subsequently, Khong et al. (2016) used a 6-seconds sliding window to segment the 1 minute of video signals. The time interval between the sliding window was 0.5 seconds. Each of the segmented 6 seconds video signals was transformed to PSD using FFT for estimating the PR. In other words, the researchers estimated the PR measurement every 6 seconds of the video signals.

As a concluding remark, the majority of the available research implemented the frequency domain analysis for measuring the PR except Khong et al. (2017) who utilised the time domain analysis of the video images for estimating the HBR. Khong et al. (2017) had presented a research for measuring human blood pressure with the non-contact video image processing techniques. In addition, the researchers also showed that analysing the 10 seconds video signals with the time domain analysis is feasible to extract the PR data. From the findings of Khong et al. (2017), it shows that the time domain analysis enables not only the measurement of PR but blood pressure as well.

Other than the consumer level webcam and digital camera, the feasibility of using the smartphone camera in measuring physiological parameters had also been researched. Kwon et al. (2012) utilised the front camera of an iPhone 4 for the remote recording of facials of 10 subjects separately from 0.3m distance to measure their PR. These videos were recorded at the rate of 30 fps for a minute. During the video recording process, the subjects were requested to sit still and stare at the middle of the screen. As an illumination condition, the investigation was conducted indoors with sufficient sunlight. Kwon et al. (2012) had utilised the algorithm of Poh et al. (2010) with MATLAB software for processing the recorded video. Since the researchers acquired a clearer frequency using the highest peak signal of the raw green colour channel, the researchers also concluded that obtaining raw signals of the green colour channel has better performance over those of the ICA approach in selecting the apt component for the PR measurement. Even though the algorithm developed by Kwon et al. (2012) had not yet been implemented in the smartphone, it is validated that the quality of the embedded smartphone camera is competent for capturing the essential signal for the PR measurement.

The camera of smartphone can be used to possibly capture the video images remotely for the PR measurement; it is also able to collect the video images in contact basis for the PR measurement. The researchers of Sukaphat et al. (2016) successfully developed an android application to measure the PR from the subject’s fingertip that was gently placed on the embedded camera. As the illumination source, the flashlight of the smartphone was used during the video recording process. From these studies, the researchers proved that the processor and camera on the smartphone nowadays are already sufficient to process video signals for the PR measurement. Since the mobile device is more portable, user friendly and popular, its usage for estimating more physiological parameters should be explored in the future. If the developed application can extract multiple physiological parameters at a non-contact basis, it will be very constructive because contact-based concept device limits the mobility and working ability of the subject. Furthermore, if the finger pressure applied on the camera lens is inappropriate, it could also lead to inaccurate results. From the reviews, the studies that used PPG imaging techniques for the PR measurement are summarised in Table 5.

As a concluding summary of these reviews, a majority existing of studies have utilized the spectral analysis to extract the PR from the captured videos. Generally, the

Table 5
Summary of the studies using PPG imaging technique for HBR measurement

Study & Year	Camera	Light Source	ROI	Contact	Remarks
Zheng & Hu (2007); Hu et al. (2008)	Consumer level digital camera	LED (660 nm, 840/870 nm and 905/940 nm)	Finger	No	- Only obtain PPG signals
Takano & Ohta (2007)	Consumer level digital camera	Ambient Light	Cheek	No	- Frequency domain spectral analysis
Verkruysse et al. (2008)	Consumer level digital camera	Ambient Light	Facial	No	- Frequency domain spectral analysis
Poh et al. (2010); Lewandowska et al. (2011)	Webcam	Ambient Light	Facial	No	- Implemented BSS method - Frequency domain spectral analysis
Kwon et al. (2012)	Smartphone front camera	Ambient Light	Facial	No	- Implemented BSS method - Frequency domain spectral analysis
Sukaphat et al. (2016)	Smartphone Camera	Flashlight	Finger	Yes	- Android based
Zhao et al. (2013)	Near-infrared enhanced Camera	Ambient & LED 830 nm	Facial	No	- Implemented BSS method - Frequency domain spectral analysis
Macwan et al. (2018)	Webcam	Fluorescent & Ambient light	Facial	No	- Implemented BSS method - Frequency domain spectral analysis
Tarassenko et al. (2014)	Digital video camera	Fluorescent & Ambient light	Facial	No	-Implemented Auto-regressive model and pole cancellation - Frequency domain spectral analysis
Khong et al. (2016)	Webcam	Fluorescent & Ambient light	Facial	No	- Frequency domain spectral analysis
Khong et al. (2017)	Webcam	Fluorescent & Ambient light	- Facial - Chest	No	- Time domain spectral analysis
van der Kooji & Naber (2019)	Webcam	Fluorescent light	- Facial - Wrist - Calf	No	- Implemented Improved Semi BSS method - Frequency domain spectral analysis
Gudi et al. (2020); Perepelkina et al. (2020); Zhan et al. (2020)	Webcam / Video Datasets	Video Datasets	- Facial	No	- Implemented learning-based method CNN for better signal acquisition - Time domain spectral analysis

main downside of using the spectral analysis is the necessary choosing of the correct peak frequency for representing the HBR. Hence, researchers have suggested the time domain analysis to be used for processing the signals of video in measuring the PR and it is also suitable in measuring the blood pressure. For choosing the right signal of the video, both the raw green colour channel or applied BSS method are also capable in providing the accurate PR estimations. Yet, Zhao (2016) also stated that BSS method is highly complex and heavy computation is required particularly when the captured signals have been mixed with many independent sources. Therefore, many studies had abandoned the BSS method and only implemented the raw green colour channel for estimating the PR. Based on the reviews, it can be concluded that the videos which are captured under the light sources with specific wavelength (i.e., natural ambient light or fluorescent light) are also adequate in providing the PR measurement.

ISSUES AND CHALLENGES

Although the ECG, the oscillometric method and the PPG, either in contact or non-contact methods, have been used to obtain the HBR, these methods have its own advantages and challenges. When there is a challenge, there will be an opportunity to come up with a solution to counter it. Hence, Table 6 illustrates the advantages and challenges of the respective methods for measuring the HBR. Furthermore, the possible solutions to counter the challenges are shown in Table 6 for future development so that a more convenient, simple, comfortable and accurate method can be applied to obtain the HBR measurement.

Table 6
Advantages, challenges and the solutions of HBR measurement methods

Methods	Advantages	Challenges	Solution
ECG	Non-invasive, reliable and standard method for diagnosing heart activities (Serhani et al., 2020)	Users have to learn the method to operate the monitoring device and placement of electrodes (Aljuaid et al., 2020)	Embedded the electrodes in T-shirts or bed sheets (Bianchi et al., 2010)
		Discomfort or skin irritation in measuring HBR due to the adhesive gel electrodes attachment (Karaoguz et al., 2019)	Developed washable textile electrodes (Ankhill et al., 2018). However, further research is required for the design of wearable devices
		ECG signal quality because it is measured in millivolts and contaminates with noises such as powerline interference, baseline wander, motion artifacts, and electromyographic noise (Kher & Vidyanagar, 2019)	Require efficient filtering and amplifying techniques (Mohaddes et al., 2020)

Table 6 *(continue)*

Methods	**Advantages**	**Challenges**	**Solution**
		Only one person's reading can be taken at the same time	This challenge is still unsolved.
Oscillometric method	Non-invasive and can measure blood pressure as well	Intermittent measurement not suitable for continuous HBR measurement (Kebe et al., 2020)	This challenge is still unsolved. PPG method is more comfortable way for continuous HBR measurement (Tjahjadi et al., 2020)
		Readings are very sensitive to the posture of the body and arm, motion artifacts (Forouzanfar et al., 2015)	This challenge is still unsolved. However, advance the filtering techniques can help in reducing the effect of motion artifacts and identifying the true pulsation (Forouzanfar et al., 2015).
		Only one person's reading can be taken at the same time	This challenge is still unsolved.
PPG (contact)	Non-invasive and simple to use (Castaneda et al., 2018)	Contact based with wired sensors might cause the discomforts	Non-contact based of using 2 dimensional image matrix for PR measurement (Tamura, 2019).
		Susceptible to motion artifacts caused by movements (Castaneda et al., 2018)	The time and frequency domain signals are filtered mathematically and statistically to eliminate the low frequency of motion artifacts for the signals (Tamura, 2019).
		Insufficient or excessive contact force will influence the quality of the PPG signals (Tamura, 2019).	Correction factors have been proposed to compensate the contact force for a PPG signal but this factor has wide variations among individuals. Hence, a miniaturized thermo-pneumatic type force regulator was designed to regulate the contact force (Sim et al., 2018).
		Infrared light penetrates deeper into the skin but its low intensity has little pulsatile action (Tamura, 2019).	Developed high-power LED and enabled use of green light has better results in a pulsatile action (Tamura, 2019).
		Typically worn on the fingers because of its high signal amplitude can be obtained. However, it is not perfect suited for continuous sensing because the involvement of the fingers in most daily activities (Tamura, 2019).	Wearable PPG devices on different measurement site have been developed. Wristwatch-type PPG device has been developed recently (Tamura, 2019).
		Only one person's reading can be taken at the same time	This challenge is still unsolved.

Table 6 *(continue)*

Methods	Advantages	Challenges	Solution
PPG (non-contact)	Non-invasive, non-contact mode for long distance measurements and possible to obtain multiple person's HBR at the same time (Tamura, 2019).	Motion artifacts (Sinhal et al., 2020)	Applied BSS method to remove the temporal noise source caused by motion artifacts (Deng & Kumar, 2020).
		Ambient light illumination (Sinhal et al., 2020)	Recent studies also explore the functions of the individual R, G and B color channels for normalizing the color of the illumination (Deng & Kumar, 2020).
		Compressed video for faster processing might lose the information resulting in an inaccurate PR estimation (Sinhal et al., 2020)	Optimized the images before measuring the PR (Sinhal et al., 2020)
		Video images are being captured with multiband spectrum, so it is challenging to identify the suitable spectrum for signal estimation (Sinhal et al., 2020)	Many contemporary studies focus on analysing the visible light spectrum (Sinhal et al., 2020)
		To obtain multiple persons' readings at the same time	Apply face tracking algorithm for multiple person's readings
		Signal quality in leading inaccurate PR measurements (Perepelkina et al., 2020)	Apply learning-based method can enhance the signal quality (Gudi et al., 2020, Zhan et al., 2020 and Perepelkina et al., 2020)

Recently, other problems such as a decreased in the SNR of the PPG signals for the dark skin and aging skin has arisen. This is due to the fact that the number of melanocytes in thinner skin and wrinkles can change the optical properties of skin. Learning-based methods have been designed to learn which sections in the image correspond to the PR. This method does not require any prior knowledge and it will learn the PPG mechanism from scratch. Gudi et al. (2020), Zhan et al. (2020) and Perepelkina et al. (2020) are the recent researchers who used the learning-method of convolution neural network (CNN) to detect the PPG signal from video. The proposed learning-based method can not only accurately estimate the PR from the PPG signals but its performance can be improved by increasing the size of the training set for adapting to various skin conditions such as dark skin and ageing skin. By implementing the learning-based method, the PPG signal quality can be improved by avoiding making the false decision when an invalid PR is extracted from the untrustworthy PPG signals. However, the disadvantage of the learning-based method is that it requires a large training set and significant computation time when dealing with complex models. Since the PPG analysis is based on a signal processing task, the use of a trainable system with no prior knowledge gives opportunity for efficiency improvement because previous studies already revealed that the PR signal is embedded in average skin colour changes.

CONCLUSION

The HBR refers to the speed of the heartbeats. It is one of the most essential vital signs in indicating the general state of health of a person. For instance, cardiac arrhythmia is detected by examining the HBR. To date, there are three typical methods used for determining the HBR, i.e., ECG, the oscillometric method and PPG. The ECG has been termed as the gold standard for the HBR measurement because it directly measures the HBR from the heart. Although the ECG method is non-invasive and reliable, the users have to learn to operate the monitoring device and the placement of electrodes. Furthermore, the adhesive gel electrodes can cause discomfort and irritation to the skin. Hence, the oscillometric method has been introduced to measure the PR when the measurement of blood pressure is taken. Yet, the oscillometric method is not suitable for long term continuous HBR measurements. Among these three methods, the contact-based PPG technique is extensively applied in medical institutes for continuous monitoring of the PR of a patient due to its aptness. With references to the existing research and techniques, it has been noticed that the PPG method is the only technique that is excellent not only for contact based, but also the non-contact-based method for the purpose of monitoring the PR. Even though the non-contact PPG method has not yet grown maturely, it has high potential to be applied in the remote healthcare industry. In addition, the non-contact PPG imaging method is also highly potent for measuring other vital physiological parameters. From this review, it clearly clarifies that the current trend of the measuring of the HBR has evolved from a contact-based method towards a non-contact-based method especially during this emerging area in video technology. Furthermore, the learning-based method also helps in improving the signal quality for a better extraction of HBR measurements. Lastly, the issues, challenges and solutions have also been summarised in this paper.

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