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Review

Wearable Photoplethysmographic Sensors—Past and Present

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Abstract: Photoplethysmography (PPG) technology has been used to develop small, wearable, pulse rate sensors. These devices, consisting of infrared light-emitting diodes (LEDs) and photodetectors, offer a simple, reliable, low-cost means of monitoring the pulse rate noninvasively. Recent advances in optical technology have facilitated the use of high-intensity green LEDs for PPG, increasing the adoption of this measurement technique. In this review, we briefly present the history of PPG and recent developments in wearable pulse rate sensors with green LEDs. The application of wearable pulse rate monitors is discussed.

Keywords: photoplethysmography; pulse rate; reflectance; transmittance; green light; infrared light; adaptive filter; least mean square algorithm

1. Introduction

It is important to monitor the perfusion of the circulation. The most important cardiopulmonary parameter is blood pressure, but monitoring it is complicated. A second important parameter is blood flow, which is related to blood pressure. We can monitor the blood perfusion in large vessels using perfusion have been developed [1], but, unfortunately, it is difficult to find a practical device. However, the perfusion of blood flow and blood pressure can be determined easily using a pulse rate monitor.

Wearable pulse rate sensors based on photoplethysmography (PPG) have become increasingly popular, with more than ten companies producing these sensors commercially. The principle behind PPG sensors is optical detection of blood volume changes in the microvascular bed of the tissue. The sensor system consists of a light source and a detector, with red and infrared (IR) light-emitting diodes (LEDs) commonly used as the light source. The PPG sensor monitors changes in the light intensity via reflection from or transmission through the tissue. The changes in light intensity are associated with small variations in blood perfusion of the tissue and provide information on the cardiovascular system, in particular, the pulse rate. Due to the simplicity of this device, wearable PPG pulse rate sensors have been developed. This review describes the basic principles of PPG, previous and current developments in wearable pulse rate monitors with a light source, and the elimination of motion artifacts.

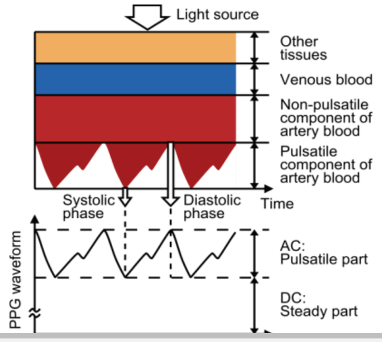
2. Photoplethysmography (PPG)

2.1. Principle of PPG

The principle of PPG has been reviewed previously [2–4], and is explained briefly here. Light travelling though biological tissue can be absorbed by different substances, including pigments in the skin, bone, and arterial and venous blood. Most changes in blood flow occur mainly in the arteries and arterioles (but not in the veins). For example, arteries contain more blood volume during the systolic phase of the cardiac cycle than during the diastolic phase. PPG sensors optically detect changes in the blood flow volume (*i.e.*, changes in the detected light intensity) in the microvascular bed of tissue via reflection from or transmission through the tissue.

Figure 1 shows an example of a photoplethysmographic waveform, consisting of direct current (DC) and alternating current (AC) components. The DC component of the PPG waveform corresponds to the detected transmitted or reflected optical signal from the tissue, and depends on the structure of the tissue and the average blood volume of both arterial and venous blood. Note that the DC component changes slowly with respiration. The AC component shows changes in the blood volume that occurs between the systolic and diastolic phases of the cardiac cycle; the fundamental frequency of the AC component depends on the heart rate and is superimposed onto the DC component.

Figure 1. Variation in light attenuation by tissue.



2.2. Light Wavelength

The interaction of light with biological tissue can be quite complex and may involve scattering, absorption and/or reflection. Anderson and Parrish examined the optical characteristics and penetration depth of light in human skin [5]; within the visible region, the dominant absorption peak corresponded to the blue region of the spectrum, followed by the green-yellow region (between 500 and 600 nm) corresponding to red blood cells. The shorter wavelengths of light are strongly absorbed by melanin. Water absorbs light in the ultraviolet and longer IR regime; however, red and near-IR light pass easily. As a result, IR wavelengths have been used as a light source in PPG sensors.

Blood absorbs more light than the surrounding tissue. Therefore, a reduction in the amount of blood is detected as an increase in the intensity of the detected light. The wavelength and distance between the light source and photodetector (PD) determine the penetration depth of the light. Green light is suitable for the measurement of superficial blood flow in skin. Light with wavelengths between 500 and 600 nm (the green-yellow region of the visible spectrum) exhibits the largest modulation depth with pulsatile blood absorption. IR or near-IR wavelengths are better for measurement of deep-tissue blood flow (e.g., blood flow in muscles). Thus, IR light has been used in PPG devices for some time [6]. However, green-wavelength PPG devices are becoming increasingly popular due to the large intensity variations in modulation observed during the cardiac cycle for these wavelengths [7–9].

A green LED has much greater absorptivity for both oxyhaemoglobin and deoxyhaemoglobin compared to infrared light. Therefore, the change in reflected green light is greater than that in reflected infrared light when blood pulses through the skin, resulting in a better signal-to-noise ratio for the green light source.

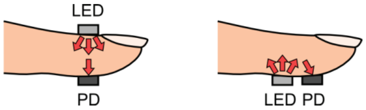
Several green-light-based photoplethysmographs are available commercially. For example, MIO Global has developed the MIO Alpha in cooperation with Philips; this measures the electrocardiogram (ECG) with 99% accuracy, even while cycling at speeds of up to 24 kmph [10]. For daily use, Omron has developed a green light pulse rate monitor (HR-500U, OMRON, Muko, Japan).

Furthermore, the use of video cameras using the signal based on the red green blue (RGB) colour space has been considered, as shown in Section 3.3. The green signal was found to provide the strongest plethysmographic signal among camera RGB signals [11,12]. Haemoglobin absorbs green light better than red and green light penetrates tissue to a deeper level than blue light. Therefore, the green signal contains the strongest plethysmographic signal.

2.3. Reflected and Transmitted Signals

The wearable PPG has two modes—transmission and reflectance—as shown in Figure 2. In transmission mode, the light transmitted through the medium is detected by a PD opposite the LED source, while in reflectance mode, the PD detects light that is back-scattered or reflected from tissue, bone and/or blood vessels.

Figure 2. Light-emitting diode (LED) and photodetector (PD) placement for transmission- and reflectance-mode photoplethysmography (PPG).



The transmission mode is capable of obtaining a relatively good signal, but the measurement site may be limited. To be effective, the sensor must be located on the body at a site where transmitted light can be readily detected, such as the fingertip, nasal septum, cheek, tongue, or earlobe. Sensor placement on the nasal septum, cheek or tongue is only effective under anesthesia. The fingertip and earlobe are the preferred monitoring positions; however, these sites have limited blood perfusion. In addition, the fingertip and earlobe are more susceptible to environmental extremes, such as low ambient temperatures (e.g., for military personnel or athletes in training). The greatest disadvantage is that the fingertip sensor interferes with daily activates.

Reflectance mode eliminates the problems associated with sensor placement, and a variety of measurement sites can be used (as discussed in the following section). However, reflection-mode PPG is affected by motion artifacts and pressure disturbances. Any movement, such as physical activity, may lead to motion artifacts that corrupt the PPG signal and limit the measurement accuracy of physiological parameters. Pressure disturbances acting on the probe, such as the contact force between the PPG sensor and measurement site, can deform the arterial geometry by compression. Thus, in the reflected PPG signal, the AC amplitude may be influenced by the pressure exerted on the skin.

Reflectance PPG sensors such as the MaxFast (Nellcor™, Mansfield, MA, USA) have been used clinically to measure continuous oxygen saturation non-invasively. Anecdotally, it gives false-positive readings occasionally. Further research is needed in this area.

3. Factors Affecting PPG Recordings

Previous research has identified several factors that affect PPG recordings, including the measurement site (*i.e.*, probe attachment site), the contact force, mechanical movement artifacts, subject posture, and breathing, as well as ambient temperature. This chapter briefly discusses these factors.

3.1. Measurement Site of Probe

The location of the LED and PD is an important design issue that affects the signal quality and robustness against motion artifacts. Therefore, suitable measurement sites must be located to optimize sensor performance. PPG sensors are commonly worn on the fingers due to the high signal amplitude that can be achieved in comparison with other sites [13]. However, this configuration is not well suited to pervasive sensing, as most daily activities involve the use of the fingers.

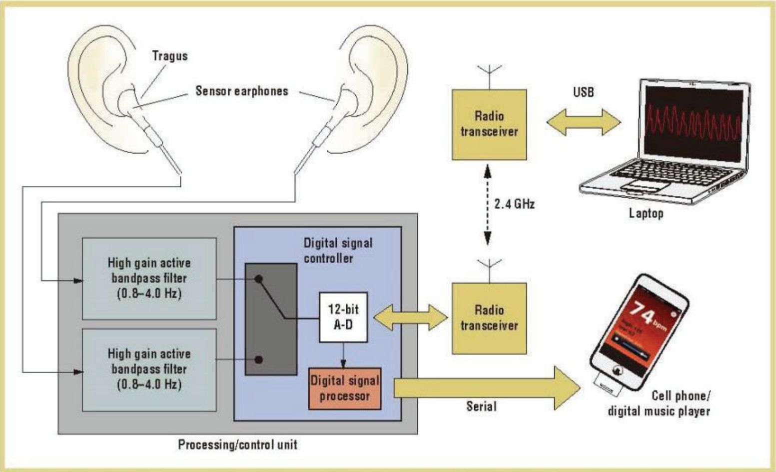
In recent years, different measurement sites for PPG sensors have been explored extensively, including the ring finger [14], wrist [15,16], brachia [9,17,18], earlobe [19–21], external ear cartilage [22–24], and the superior auricular region [25–27]. In addition, the esophageal region has been used in clinical practice [28–30]. Commercial clinical PPG sensors commonly use the finger, The perfusion values of 52 anatomical sites in healthy subjects showed that the fingers, palm, face, and ears offer much higher perfusion values compared with other measurement sites [33]; the transmitted PPG signal amplitude from the earlobe provides the largest perfusion value. In addition, earlobe sensors are easy to fabricate, and have become popular as pulse rate monitors (Table 1). However, a spring-loaded ear-clip, although effective, can become painful over extended monitoring periods. There was little improvement in the wearable earlobe PPG sensor design until the development of micro-electromechanical system (MEMS) technology. MEMS facilitated the fabrication of a lightweight, comfortable, fully integrated, self-contained sensor earpiece. For example, an earring PPG sensor with magnetic attachment to the earlobe was developed that allowed good contact for monitoring during physical activity [22].

Table 1. Key features of a wearable ear photoplethysmography (PPG) device.

Features	In-mount	CUHK	e-AR	Imperial	MIT	MIT	Pulsear	Samsung
Year published	2009 [20]	2008 [26]	2007 [19]	2009 [27]	2010 [22]	2012 [24]	2004 [23]	2009 [21]
Sensing site	Auditory canal	Inferior auricle	Superior auricle	Superior auricle	Earlobe	External ear cartilage	External ear cartilage	Earlobe
Probe attachment	Otoplastic insertion	Earhook	Earhook	Tape	Magnetic earring	Earphone	Earcup headphones	Spring-loaded clip
Wireless communication	Yes	Yes	No	No	Yes	Yes	No	No
Motion cancellation	None	None	Passive motion cancellation	None	Automatic noise cancellation	Automatic noise cancellation	PCA	Automatic noise cancellation

Earphone/earbud PPG sensors are also available and provide greater comfort for the user. In this design, a reflective photosensor is embedded into each earbud, as shown in Figure 3. The sensor earbuds are inserted into the ear and positioned against the inner side of the tragus to detect the amount of light reflected from the subcutaneous blood vessels in the region. The PPG sensor earbuds look and work like a regular pair of earphones, requiring no special training for use [24].

Figure 3. Earpiece PPG sensor (with permission [24]).



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