TECHNICAL WHITEPAPER

Wearables for Optical Cardiovascular Monitoring: Designing the PPG Sensor in the ActiGraph LEAP®

Introduction

Wearable digital health technology (DHT) has emerged as a revolutionary approach for continuous health monitoring in clinical trials and care, particularly through the use of photoplethysmography (PPG). However, PPG remains a relatively new and unfamiliar topic to many clinical researchers and healthcare providers. To help the broader clinical research community better understand the potential and proper use of PPG technology, this technical white paper aims to provide an overview of its principles, quality factors, applications, and advancements, which all factored into the design and development of the PPG sensor in ActiGraph LEAP® multisensor wearable device.

Cardiovascular Monitoring Technologies

Cardiovascular monitoring, especially cardiac monitoring, is crucial for diagnosing cardiovascular diseases, assessing physical function, monitoring adverse events, and managing overall health. Traditionally, electrocardiography (ECG) has been the gold standard for cardiac monitoring. ECG measures the electrical activity of the heart using electrodes placed on the skin, providing a precise waveform indicative of heartbeats. Despite its accuracy, ECG is often cumbersome for continuous and non-clinical use.

Other techniques such as phonocardiography (PCG), echocardiography, and impedance cardiography (ICG) also offer cardiac monitoring through different mechanisms. PCG records heart sounds using microphones, echocardiography employs ultrasound to visualize heart structures, and ICG measures thoracic electrical impedance changes related to blood flow. However, these methods also have limitations in terms of usability and cost for widespread, everyday monitoring.

Cardiovascular monitoring via photoplethysmography (PPG) has grown in prominence due to its non-invasive nature, simplicity, and cost-effectiveness. The fundamental principle behind PPG is the absorption of light by tissues in the body, where variations in absorption correlate with the pulsatile nature of blood flow. Currently, PPG is primarily applied in clinical settings for measuring heart rate (HR) and arterial oxygen saturation (SpO2), and it has become the most common approach for remote and continuous monitoring of cardiovascular function in both clinical trials and consumer wellness.

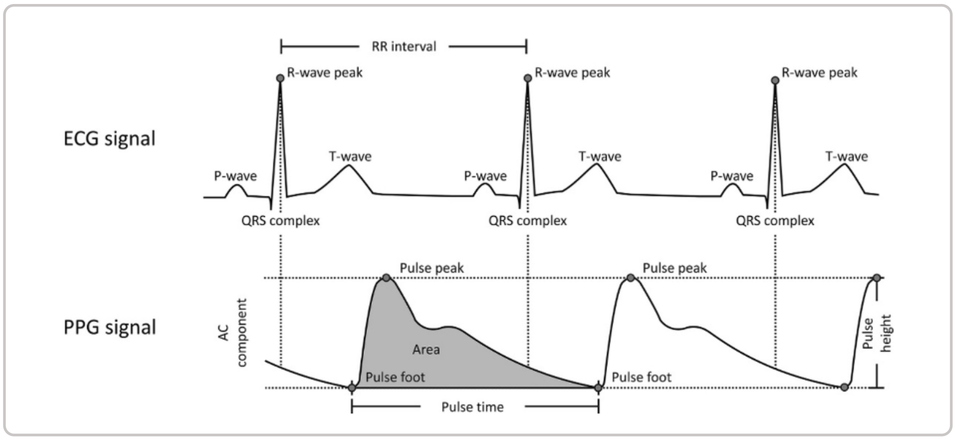

Figure 1.
A comparison of the waveforms of ECG and PPG signals collected simultaneously and their respective components.

Photoplethysmography Measurement Principles

PPG relies on the interaction of light with biological tissues. When a light source illuminates the skin, part of the light is absorbed by the tissue, while the rest is either reflected or transmitted, and captured by a photodetector. This captured light is the source PPG signal that will undergo further analysis to infer various physiological parameters.

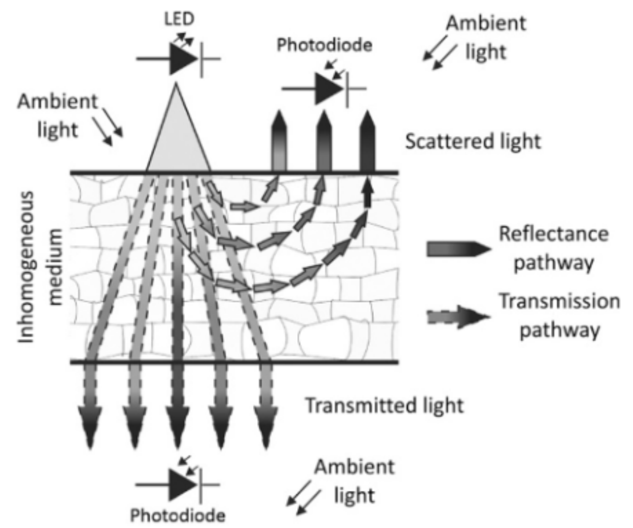

Figure 2.
Transmission vs reflectance light modes: The roles of absorption and scattering mechanisms.

Traditional PPG technology as used in clinical pulse oximeters is performed in the transmission mode. In this mode, light passes through the tissue and is detected on the opposite side. This configuration is suitable for body parts where light can traverse easily, such as the fingertips or earlobes, and is known for its high signal quality due to the minimal scattering effects. However, transmission mode is limited to specific body sites and not practical for continuous monitoring.

A more practical approach is the reflectance PPG. In reflectance mode, the light source and detector are placed on the same side of the tissue. The light penetrates the tissue, is scattered within, and a portion of the light is reflected to the detector. Reflectance mode can be used on various body locations where transmission mode is impractical, such as the forehead, chest, or wrist, making it ideal for wearable devices and continuous monitoring applications. However, it is more susceptible to motion artifacts and variations in tissue composition, which can affect signal quality. **Therefore, it is critical to ensure that the implementation of reflectance PPG considers such limitations and addresses them properly, from opto-mechanical design, electronics selection, firmware control, and algorithm development.**

Components of the PPG Signal

The PPG signal consists of two primary components: the AC (alternating current) component and the DC (direct current) component (Fig 3).

The DC component represents the constant light absorption by tissues, venous blood, and non-pulsatile arterial blood. This component varies slowly over time and is influenced by factors such as respiratory activity, thermoregulation, and overall tissue composition. The DC component serves as a baseline for the PPG signal and helps in differentiating between the pulsatile and non-pulsatile components. By analyzing changes in the DC level, it is possible to infer long-term trends in tissue perfusion and hydration status. Additionally, the DC component can provide insights into the venous blood volume and its variations, which are essential for understanding the overall hemodynamic status of the patient.

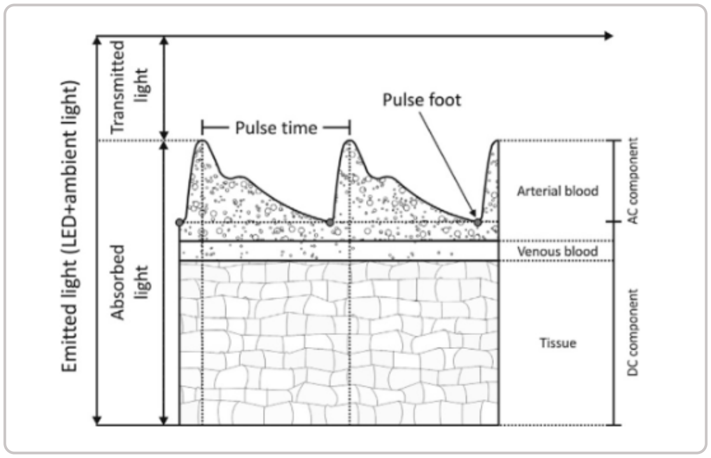

Figure 3. Simplified representation of the components of the PPG signal. The AC component due to pulsating arterial blood absorption and the DC component due to a sum of arterial blood, venous blood, and other tissues are displayed.

The AC component represents the pulsatile changes in blood volume with each heartbeat. It is superimposed on the DC component and reflects the dynamic aspect of blood flow in the arteries. This pulsatile signal is directly correlated with the cardiac cycle and provides valuable information about heart rate and arterial blood volume. The AC component is particularly sensitive to the arterial blood flow, making it a reliable indicator of cardiovascular health. Variations in the AC signal can indicate changes in stroke volume, arterial stiffness, and peripheral vascular resistance. Therefore, analysis of the AC component can provide insights into various cardiovascular conditions and aid in early diagnosis and monitoring.

Wavelength of the Light

The interaction of light with tissue varies significantly with wavelength. Tissue constituents like water, melanin, and hemoglobin have specific absorption characteristics at different wavelengths. For instance, water transmits wavelengths shorter than 950 nm efficiently, while melanin absorbs wavelengths shorter than 500 nm strongly. Hemoglobin, the primary blood constituent, has absorption characteristics that vary with its oxygenation state, impacting PPG measurements. The absorption spectra of these constituents must be considered when selecting wavelengths for PPG applications to optimize the accuracy and reliability of measurements.

Key Factors Affecting the Quality of PPG Signals and Design Considerations

PPG signals are influenced by several factors that can affect their quality and reliability. Especially in the application of reflectance PPG, it is critical to understand these factors and address them in the design of PPG technology as much as possible to ensure the quality of raw PPG signals.

Sensing Factors

Sensor Setup and Design: The quality of PPG signal is heavily dependent on the design and implementation of the sensing setup. This includes the type and amount of emitted light, the coupling between the skin and the optical probe, and the response of the photodetector. Proper sensor geometry and ergonomics are crucial to minimize optical shunting, where light travels directly from the emitter to the detector without penetrating the biological tissue. Additionally, ambient light interference must be minimized through adequate sensor design.

Emitter-Detector Distance: The distance between the light emitters and detectors is a critical factor. Optimal distances are necessary to balance tissue penetration with the intensity of the injected light. For infrared light, distances of 6-10 mm are generally optimal, while for green light, around 2 mm is preferred. This ensures sufficient photon penetration and detection.

Measurement Sites: The choice of measurement site also impacts signal quality. Common sites include the fingertip, earlobe, upper arm, and wrist. The site must be selected based on factors such as tissue composition, presence of large arteries, and susceptibility to movement artifacts. The wrist is the most convenient location for everyday use, but signal quality might not be as good as other sites such as upper arm.

Cardiovascular Factors

Blood Volume and Flow: Variations in blood volume and flow, influenced by cardiovascular health, directly affect the PPG signal. Conditions such as hypertension, arrhythmias, and other cardiovascular diseases can alter the amplitude and morphology of the PPG waveform.

Vascular Compliance: The elasticity of blood vessels, which can change with age or disease, affects the pulsatile component of the PPG signal. Decreased vascular compliance can lead to changes in the waveform's shape and amplitude.

Biological Factors

Tissue Characteristics: The inherent properties of the tissue, such as blood content and skin pigmentation, impact the absorption and scattering of light, thus affecting the PPG signal. Melanin, for instance, can absorb light, reducing signal amplitude in individuals with darker skin.

Light Compensation: If the device does not capture sufficient light signals due to increases tissue absorption, the raw PPG signals are compromised in a way that is difficult to rectify post collection. Therefore, it is necessary to address this impact at the source of data collection and ensure that the captured PPG signals meet the required signal-to-noise ratio.

Minimizing Motion Artifacts

Movements, whether voluntary or involuntary, can introduce artifacts into the PPG signal. These artifacts result from changes in tissue composition, relative motion between the sensor and the skin, and changes in the pressure between the sensor and the skin. Given the complexity of tissue-light interactions, the impact of movements can cause non-linear distortion in the PPG signals that are difficult to address by signal processing. Therefore, the design of the optical components should aim to minimize motion artifacts from the source of data collection.

Optomechanical Design: The mass of the measurement system should be low to reduce inertial forces causing skin-sensor displacement. The probe should also create friction with the skin to reduce relative motion. Proper sensor fitting is essential, ensuring sufficient stiffness and adequate pressure to maintain an optimal optical interface without excessive force that could compress blood vessels and cause discomfort. Additionally, due to the nonuniform distribution of blood vessels, small displacements of the optical components can drastically alter the signal's amplitude, increasing sensitivity to motion artifacts.

Sensor Attachment: The method of attaching the sensor to the body can significantly influence the susceptibility to motion artifacts. Secure and comfortable attachment methods that minimize relative motion between the sensor and the skin are essential for high-quality PPG measurements.

Signal Processing: Advanced signal processing techniques are necessary to filter out noise and motion artifacts from the PPG signal. Algorithms for motion artifact correction and heartbeat detection are critical to obtaining accurate heart rate and heart rate variability measurements.

Signal Processing and Analysis: The raw PPG signal requires extensive processing to extract meaningful physiological information. Signal processing techniques are employed to filter noise, enhance signal quality, and analyze the underlying physiological parameters. Typically, the processing scheme of the optical signals involves three main steps, namely the enhancement or suppression of artifacts, the spectral estimation, and the robust estimation of the targeted measurements.

Applications of PPG

PPG technology has a wide range of applications in clinical and non-clinical settings, from critical care monitoring to wearable fitness devices. Beyond the basic function of heart rate monitoring, we here discuss some of the more advanced applications of PPG technology.

Heart Rate Variability (HRV) Monitoring

PPG technology is extensively used to measure Heart Rate Variability (HRV), which is the variation in time intervals between consecutive heartbeats. HRV is an important indicator of autonomic nervous system activity, reflecting the balance between sympathetic and parasympathetic influences.

PPG-derived HRV analysis involves calculating time-domain parameters such as the standard deviation of inter-beat intervals (SDNN) and the root mean square of successive differences (RMSSD). Frequency-domain analysis decomposes the HRV signal into spectral components, typically low-frequency (LF) and high-frequency (HF) bands. The LF/HF ratio provides insights into autonomic balance, helping to assess stress and recovery states.

Atrial Fibrillation Detection

PPG technology is also effective in detecting atrial fibrillation (AF), a common cardiac arrhythmia characterized by irregular and often rapid heartbeats. AF detection using PPG involves analyzing the irregularity and variability in the pulse waveform. Algorithms can identify the chaotic and unpredictable nature of AF, distinguishing it from normal sinus rhythm and other arrhythmias.

Wearable devices equipped with PPG sensors can continuously monitor the heart rate and rhythm, providing early detection of AF episodes. Early detection is crucial for timely medical intervention, potentially preventing complications such as stroke and heart failure.

Pulse Oximetry

Pulse oximetry is one of the most well-known applications of PPG technology. It measures blood oxygen saturation (SpO2) by analyzing the absorption of light at two different wavelengths (usually red and infrared) through pulsating arterial blood. The ratio of light absorption during the pulsatile and non-pulsatile phases allows for the calculation of SpO2.

Pulse oximeters are widely used in clinical settings to monitor patients' oxygen levels and are essential in critical care, surgery, and managing chronic respiratory conditions. Portable pulse oximeters and those integrated into wearable devices have also become common, allowing for continuous monitoring of SpO2 in various settings, including home care and sports.

Blood Pressure Estimation

Non-invasive blood pressure estimation using PPG technology is gaining traction. The relationship between the PPG waveform and arterial blood pressure is leveraged to estimate blood pressure values. Techniques such as pulse wave velocity (PWV) and pulse transit time (PTT) are commonly used, where the speed of the pressure wave traveling through the arteries correlates with blood pressure.

PPG-based devices can provide continuous blood pressure monitoring without the need for traditional cuff-based methods. This continuous monitoring is particularly useful for managing hypertension and assessing cardiovascular risk in real-time.

Sleep Staging

PPG signals can also substantially improve the accuracy of wearable-based sleep monitoring. Traditional actigraphy primarily uses the accelerometer or motion to detect sleep and wake states, which suffers from low specificity and low accuracy for sleep staging. With the availability of PPG, a wrist-worn wearable can now leverage the change to physiology as our bodies go through different stages of sleep. With the incorporation of heart rate, or directly PPG raw waveform using a deep learning approach, wearable devices can detect sleep stages at a much higher specificity and accuracy.

Conclusion

Photoplethysmography is a versatile and noninvasive optical technique with broad applications in clinical and consumer health monitoring. Its ability to provide real-time insights into cardiovascular health, coupled with its ease of use, has made it an essential tool in modern healthcare. As technology advances, addressing challenges related to motion artifacts, skin tone variability, and sensor placement will further enhance the accuracy and reliability of PPG measurements.

The future of PPG lies in its integration with other physiological monitoring technologies and the development of advanced algorithms for comprehensive health assessment. By combining PPG with data from other sensors, such as electrocardiography (ECG) and accelerometers, it is possible to create robust health monitoring systems that offer a holistic view of a person's health.

With continuous innovation and research, PPG technology will continue to evolve, unlocking new possibilities for improving health outcomes and promoting proactive health management. Its potential to provide accessible, real-time health monitoring makes PPG a cornerstone of modern healthcare, benefiting both clinical practice and everyday wellness.

ActiGraph™

ActiGraph is pioneering the digital transformation of clinical research. We empower biopharma companies to unleash the potential of big data and AI with a device-inclusive digital trial platform backed by proven operational, scientific, and regulatory expertise. Used in nearly 250 industry-sponsored clinical trials and appearing in over 25K published scientific papers to date, ActiGraph is the most experienced and trusted wearable technology partner in the industry.

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