Photoplethysmography (PPG): State-of-the-art methods and applications

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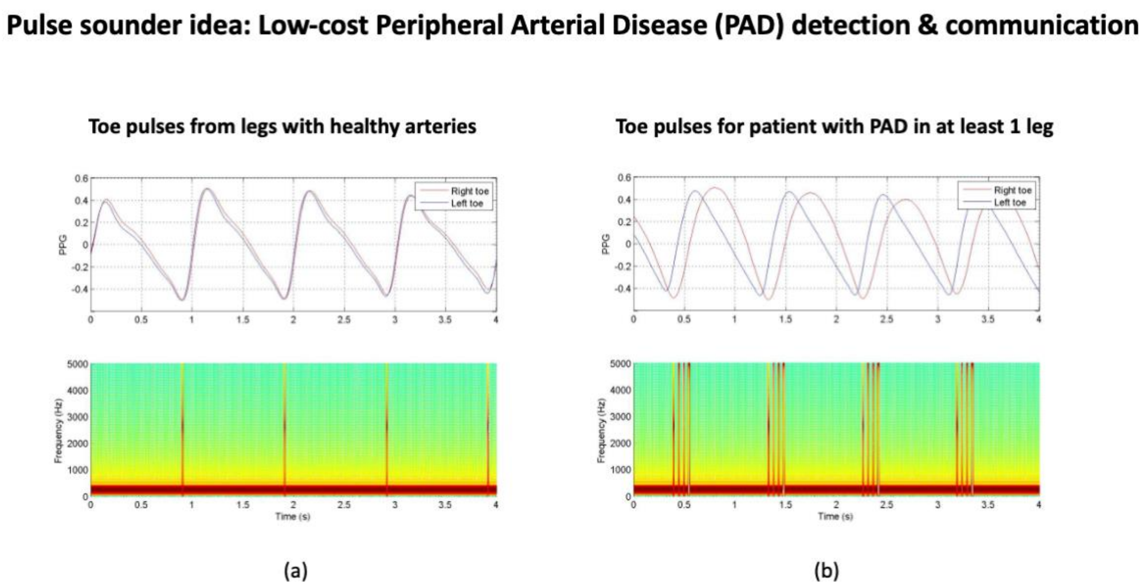

Figure 1. (a) Example bilateral great toe PPG pulses from a healthy control subject and corresponding visualization using the spectrogram representation for the first 4 s of the study window. For each heartbeat with normal pulse risetimes a single 5 kHz sound tone is generated. These sounds can easily be communicated both audibly (and/or visually) to the operator. In this subject the reference Ankle Brachial Pressure Index (ABPI) was normal for each leg. (b) Example bilateral great toe PPG pulses from a patient with Peripheral Arterial Disease (PAD) and the corresponding visualization using the spectrogram representation. The risetime for the right leg is clearly elongated (ABPI abnormal) for all heartbeats, each having a train of four distinct 5 kHz tones. From Allen and Hedley (2019). This approach of detecting and communicating PAD could be extremely low-cost when based on PPG sensor technology.

Welcome to this focus collection of Physiological Measurement on Photoplethysmography and state-of-the-art methods and applications.

Photoplethysmography (PPG) is a low-cost vascular optics technique that can be used to detect blood volume changes in the microvascular bed of tissue with each heartbeat. It is often used non-invasively at the skin surface but can also be configured for non-contact measurements using imaging PPG. The PPG waveform comprises a pulsatile ('AC') physiological waveform attributed to synchronous cardiac changes in the blood volume with each heartbeat, superimposed on a slowly varying ('DC') baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity, and thermoregulation. Although the origins of these PPG components are still not fully understood, it is generally accepted that they can provide valuable cardiovascular information (Allen, 2007).

Globally, there has been a rapid growth in research and development activities in PPG, particularly with sensor development, measurement protocols, signal processing, and a wide range of healthcare applications. The ease of acquiring PPG signals has contributed dramatically to the popularity of this relatively simple technology in recent years - especially in the field of wearable devices and digital e-health systems. Also, the current advances in optical components enable the extreme miniaturisation of such sensors. In addition, the recent advancements in signal processing techniques, including machine learning (ML) and artificial intelligence (‘AI’), have also opened up exciting new horizons for PPG-based sensing and medical diagnostics.

This focus collection of Physiological Measurement showcases, through 19 articles (17 Full Papers, 1 Topical Review and 1 Note. The paper by Lin et al (2020) winning the 2021 IoP / IPEM Martin Black award), explored the diversity of contemporary clinical and clinically related applications of PPG. A wide range of topics are covered in these sixteen articles, including the origin of PPG and light interaction with tissue, multi-wavelength PPG, relations of PPG with haemodynamics, wearables, digital health, advances in PPG imaging, standardization approaches in the technique, PPG morphology analysis, and feature extraction and their association with disease diagnostics, multi-site PPG measurement and analysis, machine learning and AI applied to PPG signal analysis, cardiovascular risk stratification, global health applications, clinical physiological monitoring including blood pressure, heart rate, cardiovascular and pulse rate variability and respiration, autonomic function monitoring, vascular assessments of aging and occlusive peripheral arterial disease (PAD), sleep study and tissue viability assessments, as well as techniques for PPG artefact rejection.

Cardiovascular disease is still regarded as the number one killer, and a number of articles in the collection show the great potential of PPG for making a global impact on this disease. Allen et al (2020) in ‘Age-related changes in pulse risetime measured by multi-site photoplethysmography’ analysed multi-site PPG measurements from head to foot (3 bilateral pairs of sites: ear lobes, index fingers and great toes) to quantify the age-related vascular increases in rise time. The research clearly showed the impact of the heart rate on the risetime measure for use in ageing and PAD detection. Allen et al also published 2 different methods of detecting occlusive PAD. The first method uses a novel ‘pulse sounder’ (could also be a ‘visualizer’ without the need for sound, or could be both sound and visual) which communicates disease detected by audio-encoding with each heartbeat whether either great pulse risetime is normal or elongated (Allen and Hedley, 2019. See Figure 1), providing the capability for a device to be extremely low-cost, fast and offer accessible testing. The second method employs a novel deep learning (‘AI’) approach for PAD detection, which utilises wavelet-generated spectral images for toe PPG signals over the ‘AC’ and ‘DC’ frequencies, with good performance obtained using a transfer learning approach (Allen et al, 2021). Ouyang et al (2021) (‘The use of multi-site photoplethysmography (PPG) as a screening tool for coronary arterial disease and atherosclerosis’) explored the use of a smartphone based three-site PPG device as a screening tool for coronary artery disease and atherosclerosis, deriving pulse wave regional velocities from segmental site measurements, and comparing to normal.

For cardiovascular assessment, it is also essential to develop new blood pressure measurement techniques, making them more portable, easier to use, and where possible to eliminate the need for an arm pressure cuff. Shalom et al (2020) (‘Systolic blood pressure measurement by detecting the photoplethysmographic pulses and electronic Korotkoff-sounds during cuff deflation’) compared arm cuff-based BP measurements from finger PPG and more traditional Korotkoff sound measurements, with noise resilience added through tracking the contralateral limb PPG measurement. Good agreement was found between techniques. Lin et al (2020) in ‘Investigating the physiological mechanisms of the photoplethysmogram features for blood pressure estimation' investigated the physiological mechanisms of the PPG features for blood pressure measurement, ultimately to include this knowledge about pulse features into a BP estimation model to track changes in the cardiovascular state for specific conditions in order to improve the robustness of the model.

Cardiovascular variability was presented by Mejía-Mejía et al (2020) in the paper entitled ‘Pulse rate variability in cardiovascular health: a review on its applications and relationship with heart rate variability’. This research found that the relationship between heart rate variability (HRV) and pulse rate variability (PRV) is not entirely understood yet and that PRV might be influenced not only due to technical aspects but also by physiological factors that might affect the measurements obtained from the pulse-to-pulse time series extracted from pulse waves. Hence, PRV must not be considered as a valid surrogate of HRV in all scenarios, and care is needed if they were to be used interchangeably. Signal quality is very important to help facilitate reliable analysis of the PPG waveform and its variability, for example in using modern machine learning approaches to detect cardiac arrhythmias such as atrial fibrillation (Pereira et al (2019) with 'Deep learning approaches for photoplethysmography signal quality assessment in the presence of atrial fibrillation').

The use of PPG for clinical monitoring was also covered in 2 specific applications: sleep staging using a combined PPG and actigraphy-based classification approach with transfer learning (Qiao et al (2021) 'Transfer learning from ECG to PPG for improved sleep staging from wrist-worn wearables'), (Motin et al (2020) 'Photoplethysmographic-based automatic sleep-wake classification using a support vector machine'); postoperative monitoring of free flaps tissue viability using red, infrared and green PPG signals which were in broad agreement with a commercial pulse oximeter (Kyriacou et al (2020) 'Photoplethysmography in postoperative monitoring of deep inferior epigastric perforator (DIEP) free flaps').

Two papers considered the links between respiration and PPG signals across the body: Bachler et al (2020) ('Non-invasive quantification of the effect of device-guided slow breathing with direct feedback to the patient to reduce blood pressure') investigated the changes in PPG with slow paced respiration; Lui et al (2020) ('Comparison of different modulations of photoplethysmography in extracting respiratory rate: from a physiological perspective') which investigated the strength of different respiratory modulations and the accuracy of resultant respiratory frequency estimations in different body sites (ear lobe and along the arm) and two breathing patterns.

There is a growing interest in the deployment of PPG imaging (PPGi) in monitoring and diagnostics. This was reflected by the three contributions on this topic: Paul et al (2018) ('Non-contact sensing of neonatal pulse rate using camera-based imaging: a clinical feasibility study'), Qi et al (2019) ('Robust heart-rate estimation from facial videos using Project_ICA)' who evaluated the performance of a skin reflection model from facial videos to remotely and reliably estimate heart rate, Mamontov et al (2020) ('Novel instrumental markers of proximal scleroderma provided by imaging photoplethysmography'), and Borik et al (2020) ('Photoplethysmography imaging: camera performance evaluation by means of an optoelectronic skin perfusion phantom'). These papers are illustrative of the potential of PPGi for remote, i.e., non-contact cardiovascular studies.

Finally, there is a notable paper addressing the science of PPG (Chatterjee et al (2020) 'Investigating the origin of photoplethysmography using a multiwavelength Monte Carlo model') quantifying for the first time the contributions of different tissue layers and sublayers in the formation of the PPG signal, and also a keynote standardization paper by Liu et al (2021) on 'Filtering-induced time shifts in photoplethysmography pulse features measured at different body sites: the importance of filter definition and standardization'. This paper takes a perceived rare stance in PPG published research with the message for researchers in this field to strive for better standardization in the technique, for example, by defining key measurement parameters such as digital (and/or analogue) filtering in research publications. Such an approach could support reproducibility in research.

We, the editors, hope this focus collection will give you a deeper understanding of how PPG can be applied in medicine and spark fresh ideas about how the technique might positively contribute to your clinical or associated specialism. We also finally wish to highlight the impact PPG has made on biomedical engineering. By summer 2021, it is notable that the 2007 PPG review by Allen exceeded 2000 citations (by Scopus) which is a record for the journal as well as for the mainstream biomedical engineering/medical physics journals. This focus collection and this focus collection and the new two PPG books, i.e., Elgendi (PPG Signal Analysis: An Introduction Using Matlab, CRC Press 2021) and Kyriacou and Allen (Photoplethysmography: Technology, Signal Analysis and Applications, a first holistic PPG reference, Elsevier and scheduled for late 2021), are certainly a great start for students, researchers, and scientists with different backgrounds who are interested in the PPG technology. Following the current trends of PPG based technologies, techniques, and applications we can forecast with certainty that PPG will continue to grow and enable the development of further disruptive technologies used in healthcare and wellbeing applications.

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