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REVIEW ARTICLES

Principles and role of photoplethysmography in anesthesiology and intensive care medicine

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ABSTRACT

Photoplethysmography (PPG) is a non-invasive optical method that detects blood volume changes in the skin microcirculation. Since its first description in 1938, PPG has evolved from a research tool into a key component of clinical monitoring, particularly with pulse oximetry. This narrative review summarizes the principles, waveform characteristics, contemporary theories, and future applications of finger PPG in anesthesiology and intensive care medicine. A literature search was conducted using PubMed and Google Scholar with the keywords "photoplethysmography," "anesthesiology," and "intensive care medicine." OpenEvidence AI was used as a supplementary tool. Retrieved articles were independently reviewed for relevance and methodological quality. Finger PPG signals comprise pulsatile and non-pulsatile components, reflecting the cardiac cycle. Waveform morphology is influenced by microcirculatory blood volume, arterial pressure, autonomic tone, and vascular compliance. Clinically, PPG underlies pulse oximetry and provides information on nociceptive stimuli, anesthesia depth, and sympathetic activity. Parameters such as perfusion index (PI), pulse transit time (PTT), and area under the photoplethysmographic curve (AUCPPG) have been explored to assess regional anesthesia efficacy and volume status. Emerging technologies enable continuous, non-invasive arterial pressure and cardiac output monitoring via algorithmic interpretation of PPG-derived signals. Finger PPG is a versatile, non-invasive tool with established and emerging applications in anesthesiology and critical care. Advances in signal analysis and device technology are expanding its role in continuous hemodynamic monitoring, potentially enhancing patient management and safety in perioperative and intensive care settings.

Keywords: Anesthesiology; Intensive Care Medicine; Photoplethysmography

Introduction

Photoplethysmography (PPG) is a non-invasive optical method that uses infrared light to assess blood flow within the microcirculation of the skin (1,2). The term „photoplethysmography" originates from Greek words „plethysmos", meaning „to increase", and „graph", meaning „to write". The history of PPG began in 1938, when Alrick Hertzman observed that the amount of infrared light absorbed and reflected by tissue varies according to blood volume within the examined area (1,3). The most significant clinical application of PPG emerged several decades later with the development of pulse oximetry, which remains an essential component of standard monitoring during anesthetic procedures, surgical and invasive procedures, and intensive care treatment (4). Although the basic principles of PPG are well known for almost a century, advances in signal analysis during recent decades have led to improved understanding of the physiological mechanisms underlying the finger PPG waveform (5). As methods for waveform analysis have evolved, the potential clinical applications of PPG have expanded beyond conventional pulse oximetry. Today, non-invasive PPG is used for advanced and minimally invasive haemodynamic monitoring, assessment of nociceptive stimuli and depth

of anesthesia during surgical procedures, and evaluation of sympathetic blockade during central neuraxial blocks and peripheral nerve blocks (6–10). Continued technological development may additionally contribute to further advancement of continuous non-invasive blood pressure monitoring based on finger PPG-derived parameters (11).

Methodology

This study was a narrative literature review that conducted a literature search using the keywords „photoplethysmography", „anesthesiology", and „intensive care medicine" in the PubMed and Google Scholar databases in order to identify relevant publications on the use of photoplethysmography in anesthesiology and intensive care medicine. The study was conducted from February 2026 to March 2026. The primary search terms included the aforementioned keywords used individually and in combination. Approximately 70 articles relevant to the topic were identified and reviewed. No restrictions regarding publication year were applied in the initial search process. Following the database search, an additional targeted review was conducted using OpenEvidence AI as a supplementary artificial intelligence-assisted search tool to identify additional relevant publications from the previous 10 years addressing specific subtopics within the field: regional anesthesia and photoplethysmography, advanced hemodynamic monitoring and assessment of volume status, assessment of depth of anesthesia and nociceptive stimuli, and respiratory monitoring. Articles were selected based on their relevance to the clinical application of photoplethysmography in anesthesia and intensive care settings. Both original research articles and review papers were considered. The collected literature was analyzed descriptively, with emphasis placed on current clinical applications, technological advances, and emerging monitoring strategies involving photoplethysmography. All articles identified through OpenEvidence were subsequently verified through conventional database sources, primarily PubMed and Google Scholar, before inclusion in the review, to ensure scientific validity and relevance.

Principle of photoplethysmography

A non-invasive PPG device consists of a light-emitting diode, which transmits infrared light into the tissue, and a photodetector, which senses the amount of transmitted or reflected light. When the light-emitting diode and photodetector are placed on the same side of the examined tissue, the device operates in reflectance mode by detecting light that is reflected from the tissue. When positioned on the opposite side of the examined tissue, the device operates in transmission mode by detecting transmitted light (2,5). The light-emitting diode and photodetector are specific for infrared light because haemoglobin absorbs infrared light more readily than other skin structures (7). Due to strong absorption, blood vessels reflect substantially less light during systole, compared to reflection occurring during diastole (7,12). Consequently, the systolic amplitude of the finger PPG waveform correlates with the end-diastolic phase of the cardiac cycle (6,7,12). The PPG signal consists of two components: a pulsatile alternating current (AC) component and a non-pulsatile direct current (DC) component. The AC component arises from synchronised heartbeats and consequent periodic changes in microcirculatory blood volume, whereas the DC component reflects lower-frequency physiological processes, including respiration, sympathetic nervous system activity, and skin thermoregulation. Otherwise stated, the AC component is a consequence of heart frequency and the DC component is a consequence of frequencies lower than heart frequency (7,2,13,14). Analysis of these waveform components has enabled broader clinical interpretation of PPG signals beyond conventional pulse oximetry.

Contemporary theory on the origin of the curve of finger photoplethysmography

Since Alrick Hertzman's discovery in 1938, numerous studies have confirmed an inversely proportional relationship between blood volume within the examined tissue and the amount of transmitted or reflected in-

nisms underlying the relationship between cardiovascular dynamics and changes in infrared light absorption still remain a matter of scientific debate. Kamshilin et al. proposed that cyclic changes in transmural arterial pressure during the cardiac cycle lead to elastic deformations of dermis, resulting in relative changes in microcirculatory blood volume (5,18). During systole, increased transmural pressure in large arteries leads to compression of dermal tissue. Although the dermis predominantly contains non-pulsatile capillaries, tissue compression decreases the distance between capillaries, thereby increasing relative capillary density during the systolic phase of the cardiac cycle (5,19,20). Consequently, absorption of infrared light increases during systole due to the relatively greater blood volume within the examined tissue (5). Nevertheless, it remains unclear whether variability in infrared light absorption during different phases of the cardiac cycle primarily reflects periodic changes in microcirculatory blood volume or alterations in transmural arterial pressure (5,18). This ongoing uncertainty illustrates that, although the clinical applicability of PPG is well established, some physiological mechanisms responsible for the generation of the finger PPG waveform remain incompletely elucidated.

Curve of the finger photoplethysmography

The finger PPG waveform reflects pulsatile movement from the heart toward the peripheral circulation at the site of probe placement. The shape of the PPG curve may be influenced by numerous physiological and clinical factors, including heart rhythm and heart rate, stroke volume, circulating blood volume, extremity position, autonomic nervous system activity, vascular wall compliance, and administration of vasoactive drugs (1). According to contemporary theories of PPG curve origin, individual tissue characteristics may also influence the shape of the curve (5). Such variability indicates that the interpretation of PPG waveforms may depend on multiple physiological mechanisms acting simultaneously.

The finger PPG curve consists of two main parts: the ascending component (anacrota) and the descending component (catacrota). The dicrotic notch, located on the descending portion of the curve, corresponds to closure of the aortic valve (1). A typical appearance of the finger PPG curve is presented in Figure 1 (21).

Because changes in the PPG signal may be difficult to detect at waveform inflection points, Takazawa et al. introduced automatic digital processing of the basal PPG signal in 1998 to enable calculation of parameters derived from the curve (1,22). Digital processing generates the first or second derivative of the original signal and is currently incorporated into most contemporary PPG devices (1,22). Interpretation of the PPG signal therefore, relies not only on the basal waveform itself, but also on signal processing techniques used for the extraction of curve characteristics and calculation of derived diagnostic parameters (1). Figure 2 presents the basic diagnostic structure of finger PPG analysis (23).

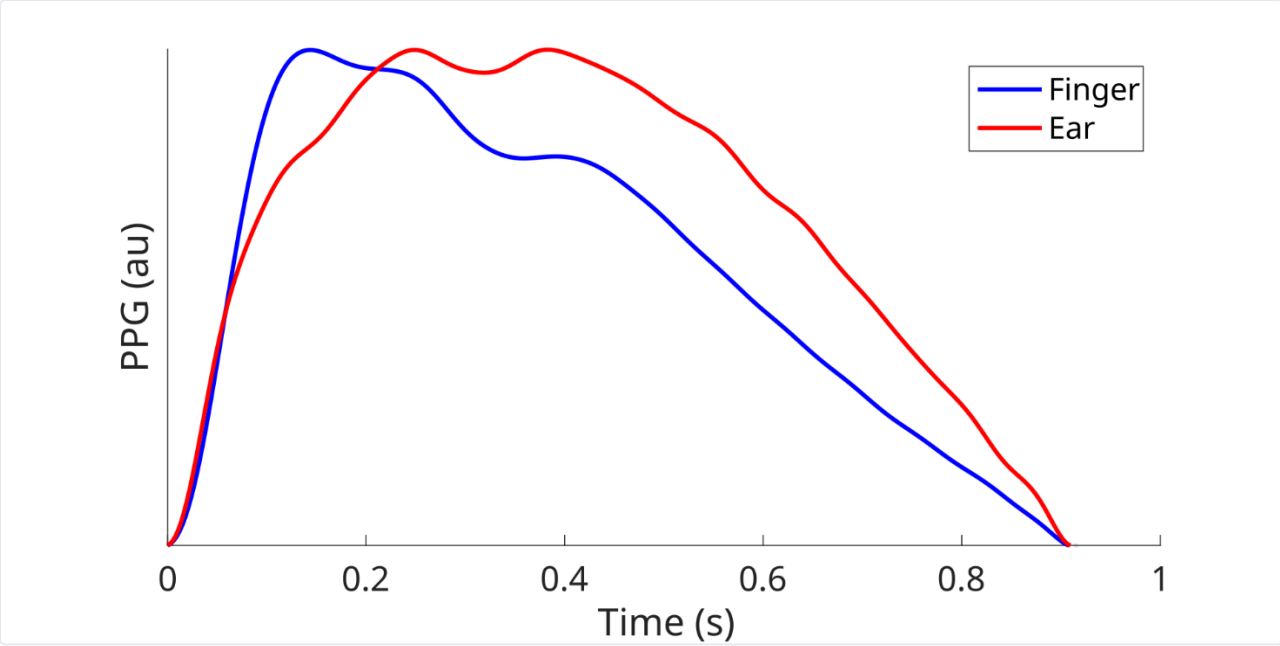

Figure 1. Finger photoplethysmography waveform. Reproduced from Charlton PH. Finger vs ear photoplethysmogram (PPG) pulse waves. Wikimedia Commons; 2016. CC BY 4.0.

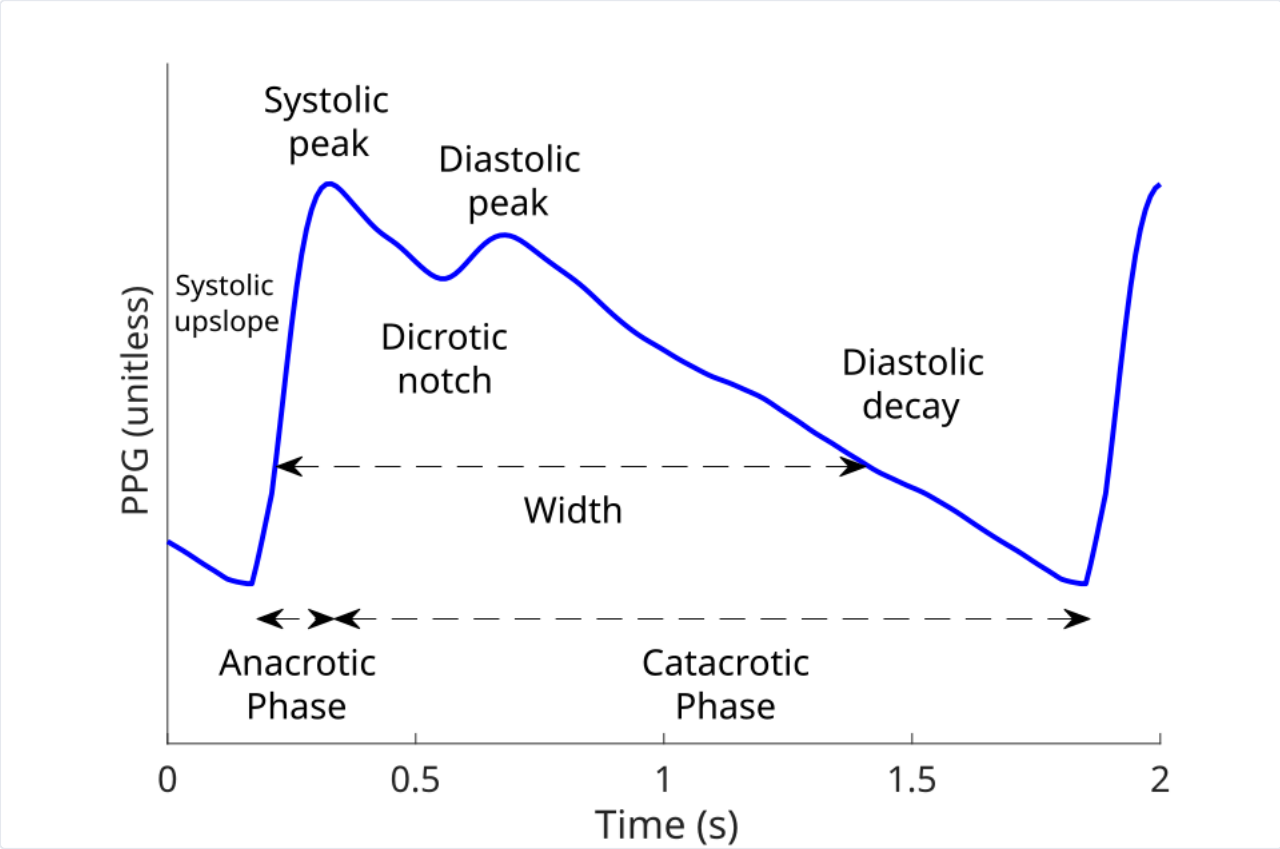

Figure 2. Diagnostic structure of finger photoplethysmography. Reproduced from Charlton PH. Photoplethysmogram (PPG) pulse wave. Wikimedia Commons; 2021. CC BY 4.0.

Respiratory monitoring

The most significant clinical application of finger photoplethysmography remains pulse oximetry, which has represented an essential component of standard monitoring during anesthetic procedures and intensive care

treatment for almost half a century. In 1972, Takuo Aoyagi discovered that tissue oxygen saturation depends on the strength of the measured pulse signal (4). Discovery led to the development of pulse oximetry, which combines finger photoplethysmography and oximetry. Oximetry is based on the Lambert-Beer law, according to which oxygenated and reduced haemoglobin differ in their absorption of red and infrared light. By combining oximetry and finger photoplethysmography, it became possible to differentiate pulsatile arterial blood from non-pulsatile venous blood and thereby indirectly estimate arterial oxygen saturation (24).

Beyond pulse oximetry, PPG has been increasingly investigated for additional applications in respiratory monitoring. PPG signals contain respiratory-induced variations (RIVs), including baseline wander, amplitude modulation, and frequency modulation, which may be used for continuous non-invasive respiratory rate estimation in both clinical and wearable device settings. Several algorithms based on these signal modulations have demonstrated results comparable with capnography and thoracic belt measurements under different body positions and low sampling rates (25–33). Nevertheless, these applications remain dependent on signal quality and processing methodology.

PPG waveform analysis has also been investigated in sleep-related breathing disorders. Variations in the PPG signal may differentiate between apneas and hypopneas during sleep, and machine learning models trained on PPG-derived features have demonstrated the ability to classify such events with reasonable accuracy (34). These findings suggest potential utility of wearable PPG devices in sleep monitoring, although broader clinical applicability continues to require further evaluation.

In addition, PPG-derived parameters have been used for assessment of respiratory effort through analysis of amplitude, baseline, and pulse transit time (PTT) modulations. Reported correlations between these parameters and airway pressure or respiratory load suggest possible application in non-invasive assessment of respiratory mechanics and upper airway dynamics (35).

Respiratory synchronous variation in the PPG waveform, including the pleth variability index (PVI), has also been utilized in the prediction of fluid responsiveness in mechanically ventilated patients (25,36). This application leverages the respiratory modulation of the PPG signal to inform hemodynamic management (25,36).

Recent technological advances have additionally enabled remote PPG-based respiratory rate estimation for telemedicine and unobtrusive monitoring in ambulatory and elderly care settings (28,29). Overall, these developments indicate expanding clinical interest in respiratory applications of PPG; however, the degree of clinical utility may vary depending on patient population, monitoring conditions, and applied signal-processing techniques (25–36).

Assessment of depth of anesthesia and nociceptive stimulus

Finger PPG has been investigated as a potential tool for assessment of anesthesia depth during surgical procedures (7). Zhang et al. compared various parameters derived from the finger PPG curve with the Cerebral State Index (CSI) during general anesthesia and concluded that finger PPG is inferior to CSI for direct assessment of anesthesia depth. However, the same study suggested that finger PPG may be useful for assessment of analgesia during balanced general anesthesia (37). Krishnamohan et al. demonstrated a significant correlation between perfusion index (PI), derived from finger PPG, and minimum alveolar concentration (MAC) values, suggesting potential utility of PI in monitoring anesthetic depth, particularly in pediatric populations (38). Nevertheless, PI primarily reflects peripheral vasodilation and sympathetic nervous system activity, both of which may be influenced by hypnotic and analgesic components of anesthesia. Consequently, the interpretation of PI as an isolated indicator of anesthetic depth may be limited.

Several studies have therefore focused on the use of finger PPG for assessment of nociceptive stimulus during surgical procedures, with reported positive correlation between the PPG-derived parameters and

ive stimulus (8,39,40). One of the most established PPG-derived parameters in this context is the surgical pleth index (SPI), which is calculated from pulse amplitude and pulse frequency obtained by pulse oximetry (41). In 2018, Choi et al. proposed the nasal photoplethysmography index (NPI) as a potential parameter for assessment of nociception during surgery and concluded that its performance was comparable to SPI in evaluating nociceptive stimulus (9).

Pulse transit time (PTT) has additionally been investigated as a marker of nociceptive response. Sigtermans et al. applied PTT during both laparoscopic and open abdominal surgery and reported successful detection of nociceptive impulses (39). Similarly, Singham et al. proposed PTT as a surrogate marker for nociceptive stimulus during gynecological surgery and concluded that PTT changes adequately reflected sympathetic nervous system responses to nociceptive stimulation and fluctuations in anesthesia depth, independently of heart rate changes (40). Beyond nociception monitoring, intraoperative trends in PTT have also been proposed as potential surrogate markers for estimation of blood loss during surgery (42).

Recent multimodal approaches integrating PPG with electroencephalographic and electrocardiographic signals using deep learning models have demonstrated additional potential for intraoperative nociception monitoring; however, these approaches have not yet become part of standard clinical practice (43). Overall, current evidence suggests that PPG-derived parameters may be more applicable for assessment of nociceptive and autonomic responses during anesthesia than for direct assessment of hypnotic depth. In comparison with electroencephalography-based monitors such as CSI, Bispectral Index (BIS), and Patient State Index (PSI), the role of PPG in direct monitoring of anesthetic depth remains more limited (8,9,39–41,43).

Regional anesthesia

The ability of finger PPG to indirectly reflect changes in systemic vascular resistance has resulted in numerous studies investigating its application in regional anesthesia. PPG-derived parameters have been used for assessment of sympathectomy following administration of peripheral nerve blocks and central neuraxial blocks, as well as for evaluation of clinical adequacy of administered nerve blocks (7,44–52).

Area under the curve of the finger photoplethysmography (AUCPPG) has been described as an indicator of changes in vascular tone (53). Babchenko et al. explained that decreased sympathetic activity following epidural block increases vascular compliance, which subsequently affects pulse wave propagation (50,54,55). Although systolic amplitude and width of the PPG waveform are more commonly investigated, several studies have evaluated AUCPPG as an independent parameter for assessment of systemic vascular resistance during anesthetic procedures. Seitsonen et al. described AUCPPG as a potential parameter for assessment of nociception during abdominal hysterectomy under balanced general anesthesia (56), while La Yang et al. proposed its possible utility in postoperative pain assessment (57). However, clinical experience with AUCPPG as an isolated monitoring parameter remains relatively limited.

Pulse oximeter perfusion index (PI) has also been investigated as a marker of sympathectomy after neuraxial blockade. Ginosar et al. examined changes in PI following epidural administration of bupivacaine and concluded that PI may represent a more sensitive indicator of sympathectomy compared with changes in mean arterial pressure and skin temperature (44). PI is calculated from pulse oximetry as the ratio between pulsatile and non-pulsatile signal components (AC/DC x 100) (58).

PTT is another frequently investigated PPG-derived parameter in regional anesthesia. Babchenko et al. demonstrated that increases in PTT after epidural administration of bupivacaine reflected sympathectomy more sensitively than conventional clinical indicators such as mean arterial pressure and skin temperature (50). Kortekaas et al. additionally proposed increasing PTT trends after axillary block as a potential marker of successful brachial plexus blockade (46). Similar approaches have been described for the assessment of successful caudal block in children and blockade of the lumbar sympathetic ganglion in neuropathic pain

treatment (48,49). Several studies have also used PTT for evaluation of sympathectomy after epidural anesthesia during surgical procedures (7,50).

In obstetric anesthesiology, PTT has mainly been investigated as a marker of cardiovascular changes after spinal anesthesia for cesarean delivery (51,52). Sharwood-Smith et al. reported that a 20% increase in PTT after spinal anesthesia predicted a decrease in mean arterial pressure greater than 10% from baseline with 74% sensitivity and 70% specificity (53). Approximately one decade later, Bolea et al. reported similar findings describing 76% sensitivity, 70% specificity, and 72% overall accuracy of PTT in the prediction of hypotension following spinal anesthesia for cesarean delivery (52). PPG-derived signals have also been successfully applied in the evaluation of sympathectomy after epidural analgesia during vaginal delivery (59).

Despite the promising results reported in multiple studies, PPG-derived parameters are still not part of standard clinical monitoring in regional anesthesia. Proposed limitations include technical barriers, complexity of signal interpretation, increased use of ultrasound guidance, and susceptibility of PPG-derived parameters to confounding factors (i.e., patient anxiety, systemic medications, etc.). Consequently, conventional clinical methods, including assessment of sensation to cold, touch, and pinprick testing, remain the standard techniques for evaluation of peripheral and central neuraxial block success in everyday clinical practice (60).

Advanced hemodynamic monitoring and assessment of volume status

Middleton et al. described the successful application of PPG for the assessment of peripheral circulation in septic patients, thereby introducing the possibility of non-invasive hemodynamic monitoring in this population (61). In this context, a case report describing the use of esophageal PPG in a patient with diffuse peritonitis additionally demonstrated potential application of PPG for assessment of hemodynamic coherence (62).

PPG-derived parameters have also been investigated for the assessment of volume status in critically ill patients. Established methods of advanced hemodynamic monitoring, including lithium dilution cardiac output (LiDCO) systems, have been used for many years to calculate parameters such as stroke volume variation (SVV) and pulse pressure variation (PPV) in order to evaluate hemodynamic response following intravenous fluid administration (10). Similarly, parameters derived from the finger PPG curve, including pulse amplitude variation (PAV) and PVI, have been proposed as non-invasive alternatives for assessment of volume status in critically ill patients (63,64).

Over recent decades, there has been substantial development of hemodynamic monitoring technologies utilizing PPG for minimally invasive or non-invasive cardiac output assessment, including previously mentioned LiDCO systems (10,65). However, it should be emphasized that several commonly used advanced hemodynamic monitoring systems, such as LiDCO, Pulse Index Contour Continuous Output (PiCCO), and FloTrac, still require placement of a peripheral arterial catheter for cardiac output calculation (66,67). In contrast, estimated continuous cardiac output (esCCO) monitoring represents a completely non-invasive approach that calculates cardiac output algorithmically by measuring PTT, also referred to as pulse wave transit time (PWTT) (68). Several reports have described successful clinical utilization of esCCO monitoring. For example, esCCO was used in one case report to detect a reduction in cardiac output following administration of epidural analgesia during vaginal delivery (69). Nevertheless, comparative clinical trials evaluating esCCO have reported conflicting results regarding its accuracy when compared with more conventional monitoring techniques (70,71). These findings indicate that, although non-invasive PPG-based cardiac output monitoring demonstrates promising potential, its clinical performance may vary depending on methodology and reference standard.

Additional PPG-based technologies include the Biobeat BB-613WP medical-grade patch-monitor, which utilizes a reflective PPG sensor and PTT analysis calibrated against cuff-based blood pressure measurements.

Clinical studies comparing this device with invasive pulmonary artery catheter measurements have demonstrated its capability for non-invasive monitoring of cardiac output and systemic vascular resistance (72).

Another example is the volume-clamp method, implemented in devices such as Finapres and related systems. These devices use finger cuffs to continuously measure arterial blood pressure and derive cardiac output from the arterial pressure waveform according to the Penaz principle. Reported measurements have shown comparability with conventional brachial pressure measurements (39).

Experimental systems integrating spectrometry, PPG, and arterial pressure measurement have also been developed. These systems combine time-resolved and wavelength-resolved optical fingertip signals under externally applied pressure in order to derive hemodynamic information from both macrovascular and microvascular circulation (73,74).

In parallel, wearable devices and bedside monitoring systems, incorporating advanced signal processing and calibration protocols, are becoming increasingly available. However, their clinical utility and accuracy continue to be evaluated against invasive reference methods (72,73,75).

Due to the possibility of estimating arterial blood pressure from PTT measured by finger PPG, continued development of continuous non-invasive blood pressure monitoring technologies may be expected in forthcoming years (7,11,19).

Conclusions

Since its initial discovery in the first half of the twentieth century, the most established clinical application of PPG has remained pulse oximetry, particularly in anesthesiology and intensive care medicine. Advancements in signal analysis and monitoring technology during the second half of the twentieth century enabled a broader understanding of the physiological principles underlying the PPG signal and contributed to the expansion of its potential clinical applications. Beyond pulse oximetry, finger PPG has been investigated for assessment of nociceptive stimulus during surgical procedures, evaluation of sympathetic blockade following peripheral nerve blocks and central neuraxial anesthesia, respiratory monitoring, and advanced hemodynamic assessment. Several studies have demonstrated promising results for these applications; however, many PPG-derived parameters continue to be primarily used in research and experimental settings rather than as part of routine clinical monitoring.

Among emerging applications, advanced hemodynamic monitoring represents one of the most significant areas of ongoing development. Numerous technologies based on finger PPG and pulse transit time analysis have demonstrated potential for minimally invasive or non-invasive assessment of cardiac output, volume status, and cardiovascular changes. Nevertheless, variability in methodology, technical limitations, and conflicting results in comparative studies indicate that further clinical evaluation remains necessary before broader standardization and implementation can be achieved.

Overall, current technological progress suggests continued expansion of PPG-based monitoring systems, including further development of continuous non-invasive arterial blood pressure monitoring derived from the finger PPG signal.

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