UDC: 616.12-008.331 DOI: 10.64854/2790-1289-2025-50-4-09
IRSTI: 76.00.00

CLINICAL PERSPECTIVES ON PHOTOPLETHYSMOGRAPHY IN IDENTIFYING THE RISK OF DEVELOPING CARDIOVASCULAR DISEASES

B. A. Bugibayeva[*] [1], A. S. Abzaliyeva [2], B. K. Abzaliyev[2], M. T. Abdirova[1], U. M. Suleimenova [2], A. M. Datkabayeva[3]

[1] Kazakhstan Medical University «KSPH», Kazakhstan, Almaty
[2] Al-Farabi Kazakh National University, Kazakhstan, Almaty
[3] Karaganda National Research University named after E.A. Buketov, Kazakhstan, Karaganda
[*]*Corresponding author*

Abstract

Introduction. This literature review focuses on modern methods for assessing cardiovascular risk using photoplethysmography and heart rate variability. Non-invasive approaches to assessing vascular wall health, arterial stiffness, heart rate, and microcirculation are discussed, along with their relationships with cardiovascular risk factors.

Objective: To analyze the potential of photoplethysmography as a non-invasive method for early detection of cardiovascular risk and to justify the need for its more widespread use in clinical practice.

Materials and methods: A search of international and domestic sources on methods for assessing heart rate variability and photoplethysmography was conducted across PubMed, Google Scholar, the Cochrane Library, Scopus Preview, eLibrary, and Cyberleninka databases. The search period was 10 years.

Results and discussion. The review revealed the potential of photoplethysmography and heart rate variability as informative digital markers that can reflect subclinical vascular changes and predict cardiovascular events. However, existing limitations are highlighted: the need for standardized signal recording protocols, variability in data quality, limited data on long-term clinical outcomes, and limited external validation of the models. The presented data support the need for further prospective studies, improved signal quality, the development of interpretable AI models, and the integration of photoplethysmography/heart rate variability with other biomarkers for a comprehensive assessment of cardiovascular health.

Conclusions. The literature review demonstrates that photoplethysmography is a promising, accessible, non-invasive method for early assessment of cardiovascular health. Photoplethysmography signal analysis allows for the detection of arterial stiffness, vascular tone, and other early subclinical changes associated with cardiovascular diseases risk. However, despite its high potential, the clinical application of this method is limited by the lack of standardized protocols, device heterogeneity, variability in data quality, insufficient clinical validation, and the predominance of cross-sectional studies without long-term outcomes.

Keywords: *photoplethysmography, heart rate variability, arterial stiffness, cardiovascular risk, artificial intelligence, digital biomarkers.*

Introduction

Cardiovascular diseases (hereinafter – CVD) remain the leading cause of death and health loss worldwide, placing a significant burden on healthcare systems and economies. According to global studies, coronary heart disease and stroke are the leading causes of mortality. At the same time, the prevalence of classic risk factors (cardio-metabolic, behavioral, environmental, and social factors) remains high and continues to increase worldwide, particularly in low-education and low-income settings. Early and accurate assessment of individual CVD risk is essential for effective primary prevention, enabling timely initiation of more intensive risk-reducing treatment and optimizing the allocation of screening resources. [1]. Analysis of modifiable (age, gender, positive family history) and non-modifiable risk factors (arterial hypertension, lipid metabolism disorders, smoking, hyperglycemia, low physical activity and obesity, etc.) explains a significant part of the risk variability in the population, leaving a residual risk, which stimulates the search for and implementation of additional markers and studies [2]. These markers include lipid profiles, indicators of renal impairment, and innovative approaches such as vascular stiffness assessment, heart rate variability (hereinafter – HRV) measurements, arterial stiffness, and genetic modification. Integration of these markers can improve risk stratification, particularly in patients with low and intermediate clinical risk [1; 2].

In a clinical context, the ability of photoplethysmography (hereinafter – PPG) analysis to extract parameters related to arterial stiffness and wave velocity, which are independent predictors of cardiovascular morbidity and mortality, is of key interest. Several studies have shown that parameters derived from peripheral PPG analysis correlate with classical measurements of aortic stiffness and can serve as non-invasive markers of vascular aging [3]. Despite the accumulated science, key challenges in risk identification remain, including the need to adapt assessment tools to population and ethnic characteristics, limitations in the availability and cost of expanded testing in primary care, and a lack of evidence demonstrating that improved predictive models necessarily translate into better clinical outcomes [4]. When studying the functional state of the heart, HRV is a key factor, which is measured using a photoplethysmograph. HRV is the variation in the time intervals between successive heartbeats. High HRV is not always better, as pathological conditions can increase HRV. CVD leads to increased HRV, which is closely associated with an increased risk of mortality [5].

PPG is a photometric method used to measure volumetric changes in the blood, as well as heart rate, pulse wave velocity, arterial stiffness, and HRV. These indicators are informative markers of cardiovascular risk and have stimulated fundamental research into the origins of PPG signals. In recent years, PPG has attracted increasing attention for its potential to assess cardiovascular health and predict outcomes. Thus, its low cost, simplicity, and the ability to be monitored in an outpatient setting make PPG a promising tool for the prevention and early detection of latent cardiovascular pathologies. The clinical, diagnostic, and therapeutic significance of HRV obtained using PPG has been established [6; 7]. Therefore, this literature review aimed to highlight the importance of encouraging healthcare organizations to adopt non-invasive diagnostic methods more actively for CVD risk assessment.

Objective: To analyze the potential of photoplethysmography as a non-invasive method for early detection of cardiovascular risk and to justify the need for its more widespread use in clinical practice.

Materials and methods

A search of foreign and domestic sources on methods for assessing HRV and PPG was conducted in PubMed, Google Scholar, Cochrane Library, Scopus Preview, eLibrary, and CyberLeninka databases. A literature search was conducted using keywords and combinations including: PPG, HRV, cardiovascular risk, non-invasive diagnostics, and arterial stiffness. The search covered the past 10 years (2015-2025 y).

The PICO method was used for a structured literature search and analysis. This framework exemplifies international best practice for conducting literature reviews and evaluating the effectiveness of diagnostic methods for prognosis. The review considered individuals with cardiovascular risk factors as the population (P), PPG as the intervention (I), other non-invasive cardiovascular risk assessment methods as the comparison (C), and the outcome (O) as the clinical significance of PPG parameters reported across various studies.

The inclusion criteria were peer-reviewed articles, original studies, and publications in English and Russian that provided qualitative and quantitative data analysis.

The exclusion criteria were conference abstracts, non-scientific sources, and articles without full text.

The selected publications were analyzed using thematic content analysis, including the systematization of methods for recording and processing PPG signals, the assessment of the clinical significance of the indicators, and the analysis of the use of artificial intelligence (hereinafter – AI) algorithms and machine learning methods for predicting cardiovascular risk. A total of 70 publications were identified, 43 of which were included in the final analysis.

These studies are part of a research project funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan, registered under number AP19677754, entitled «Development of markers and a diagnostic algorithm for the detection and prevention of early cardiovascular aging». They also constitute the initial stage of a doctoral thesis.

Results

Advances in photoplethysmography signal analysis for predicting cardiovascular disease development

The cardiovascular system (hereinafter – CVS) plays a vital and fundamental role in maintaining the human body's vital functions. Therefore, developing systems for rapid monitoring of CVS status in humans is an urgent and important task. Global and regional studies show that CVDs remain the leading cause of death and disability worldwide, with the highest burden observed in low- and middle-income countries. These studies demonstrated changes in the burden of CVDs from 1990 to 2023 and identified factors influencing these changes, including population growth, population aging, and the impact of both modifiable and non-modifiable risk factors. Aging is a major non-modifiable risk factor for CVDs, which are the leading cause of death worldwide. Cellular proinflammatory processes, which increase with age, are considered a key mechanism for accelerated vascular aging, in which the biological age of vessels outpaces the chronological age. This condition is accompanied by a sharp increase in the risk of developing CVDs and premature mortality [8; 9].

Cardiovascular aging is a multifaceted process driven by the interplay of endothelial dysfunction, extracellular matrix remodeling, vascular inflammation, mitochondrial dysfunction, and cellular senescence. As the heart and blood vessels age, structural and functional changes occur, leading to degeneration and an increased risk of CVD. These mechanisms contribute to the loss of elasticity in large arteries, the development of atherosclerosis, hypertension, and cardiac dysfunction, particularly heart failure with preserved ejection fraction [8; 10].

Both non-invasive and invasive imaging techniques, such as ultrasound, magnetic resonance imaging, and angiography, are widely used in clinical practice. However, despite their routine use, these methods are not always suitable for rapid, early screening, as they can be labor-intensive, costly, operator-dependent, and, in some cases, invasive. Contemporary studies aim to correlate the results of non-invasive and invasive assessments with the risk of developing CVD [10; 11].

There was a need for a rapid and relatively simple screening method that would be clinically acceptable. In the 1980s, PPGs were introduced into clinical practice as pulse oximeters, which revolutionized the measurement of arterial oxygen saturation and remain widely used across a variety of clinical settings. In the 2010s, this technology was integrated into consumer wearable devices, such as smartwatches and fitness trackers, which are now used daily by millions of people. Over the past decades, substantial research in the field of PPG has revealed its potential far beyond pulse oximetry, particularly with the recent development of wearable devices based on this technology. However, despite the widespread use and acceptance of PPG, the precise origin of its signal remains a subject of scientific debate [12;13].

In the 1990s, active comparisons of PPG and electrocardiogram (hereinafter – ECG) signals were conducted. Researchers found that the intervals between successive PPG peaks (PP intervals) exhibit a high correlation with ECG RR intervals ($r = 0.97$), enabling HRV assessment by PPG. The first algorithms for signal filtering and time-domain analysis subsequently emerged [13]. With advances in digital sensors and computational methods, PPG is now used to evaluate autonomic regulation parameters, including temporal- and frequency-domain indices of HRV, such as SDNN, RMSSD, and LF/HF [14; 15].

According to the literature, over the past 20 years, significant relationships have been identified between the autonomic nervous system and cardiovascular mortality, including sudden cardiac death. Although automaticity is one of the heart's intrinsic abilities, enabling electrical impulses to be generated in the myocardium without nervous stimulation, heart rhythm is now considered an integral marker of the functional state of multiple systems that maintain the body's homeostasis [15;

16]. Spontaneous fluctuations in heart rate reflect the interplay between constant influences on CVS and the responses of its regulatory mechanisms.

HRV analysis is a method to assess the activity of the cardiovascular and autonomic nervous systems. HRV is continuously regulated through complex interactions between the branches of the autonomic nervous system, including the sympathetic and parasympathetic pathways [16; 17].

Time-domain PPG indices obtained by pulse-to-pulse determination include:

PP interval (Pulse-to-Pulse Interval): intervals between successive PPG peaks; the basis for HRV analysis.

SDNN (Standard Deviation of NN intervals): reflects overall HRV; low values indicate reduced adaptive capacity of the autonomic nervous system.

RMSSD (Root Mean Square of Successive Differences): indicates parasympathetic (vagal) activity; higher values reflect greater vagal influence.

pNN50 (% of intervals >50 ms): indicates rapid vagal modulation; higher values correspond to good variability and pronounced vagal activity.

Frequency-domain analysis is divided into three spectral components:

High frequency () (0.15–0.40 Hz): reflects parasympathetic nervous system influence, primarily driven by respiratory modulation.

Low frequency (hereinafter – LF) (0.04–0.15 Hz): reflects sympathetic activity and baroreflex control.

Very low frequency (hereinafter – VLF) (0.01–0.04 Hz): associated with humoral-metabolic processes, thermoregulation, and baroreflex activity.

VLF/HF ratio (0.5-2.0): reflects the balance of central and peripheral influences on heart rhythm [14-17].

Recent studies (2019, 2020) have demonstrated that frequency-domain indices of PPG waveform variability, such as HF %, LF %, and LF/HF %, possess sufficient sensitivity and can serve as specific markers of arterial hypertension and coronary heart disease in adult men. HF % variability increases 2–5-fold in patients with arterial hypertension and up to 8-fold in patients with coronary heart disease compared to healthy individuals. Conversely, LF % variability, associated with sympathetic activity, decreases 1.5–5-fold in all patients with CVD relative to healthy controls ($p < 0.001$) [17].

A longitudinal cohort study conducted in 2024 showed that decreases in LF and HF, along with increases in LF/HF, in nocturnal PPG recordings predicted the development of hypertension and myocardial infarction over 5 years, independent of age and sex. Low HF and high LF/HF were significantly associated with coronary heart disease ($p < 0.01$). Changes in VLF were also found to serve as early indicators of endothelial dysfunction and chronic stress. These findings suggest that frequency-domain PPG parameters (VLF, LF, HF, LF/HF) represent key risk factors for the development of CVD [18; 19].

A recent British study (2024) demonstrated the feasibility of using optical PPG data, combined with deep learning methods, to predict the 10-year risk of major cardiovascular events using a minimal set of predictors: age, gender, smoking status, and PPG signals. The study provided statistically significant prognostic information on cardiovascular risk ($p < 0.05$). However, the study relied solely on UK Biobank samples and excluded key risk factors, such as blood pressure, BMI, and physical inactivity. The researchers emphasized the need for further investigation into PPG-based predictive methods [19].

A multivariate statistical analysis conducted in 2021 demonstrated that changes in HRV are associated with factors such as body mass index, coffee consumption, smoking, and chronic diseases, with statistically significant results ($p < 0.01$). Low HRV was identified as one of the primary predictors of sudden death among adults at risk for CVD and serves as an important marker for assessing the risk of heart disease [20]. Recent studies have also highlighted the value of PPG in assessing endothelial dysfunction in patients with risk factors for cardiovascular complications. Specifically, the PPG power spectral density in the 0.01–0.02 Hz frequency range was significantly lower in smokers compared to nonsmokers, but only during the endothelium-induced vasodilation phase ($p = 0.005$). This finding indicates the high sensitivity and specificity of PPG for evaluating nitric oxide-mediated vascular reactivity. Consequently, this technique shows potential for detecting early microvascular damage caused by smoking, as evidenced by reduced NO-dependent vascular reactivity [21].

The results of a three-year study showed that patients with chronic heart failure (hereinafter

– CHF) and a history of myocardial infarction exhibited increased heart rates over the study period, while the low- and high-frequency components of the HRV spectrum were lower compared to patients without myocardial infarction. Comparisons of HRV parameters between surviving and deceased patients revealed significant decreases in SDNN and LF ($p < 0.001$). Thus, a reduction in the low-frequency component of the HRV spectrum can be considered a predictive indicator for the risk of heart failure decompensation and mortality over the subsequent three years in patients with CHF. Many researchers have also explored the assessment of arterial stiffness using PPG in vivo. Several in vivo studies have focused on specific conditions, including pregnancy, obesity, and diseases such as coronary artery disease [22; 23].

Epidemiological studies have shown that increased arterial stiffness elevates pulse pressure, which can contribute to isolated systolic hypertension. Pulse pressure is also associated with coronary heart disease and cardiovascular complications in hypertensive and elderly patients (OR = 1.097, $p = 0.026$) [24]. Thus, recent studies have proven the arterial stiffness index, measured by fasting plasma glucose (hereinafter – FPG), to be an independent, genetically determined risk factor for hypertension and an independent, non-causal risk factor for coronary heart disease.[25].

In recent years, numerous methods for assessing HRV have been developed. A study by T.L Borisenko and A. V. Frolov evaluated both key linear HRV parameters (SDNN, LF/HF) and nonlinear dynamics indicators (ApEn, nonlinear LF/HF ratio). The LF/HF ratio was significantly higher in patients with atrial fibrillation, whereas patients with coronary artery disease (hereinafter – CAD) exhibited the lowest LF/HF ratio ($p < 0.001$). These data have proven valuable for characterizing autonomic balance and have become reliable markers of complication and mortality risk in patients with CVD [26].

Currently, a large body of literature provides new insights into the relationship between pulse morphology and PPG. This includes aspects such as aging, arterial stiffness, blood pressure, vascular compliance, and microvascular disease. Significant efforts are also being made to use PPG for the detection of cardiac rhythm abnormalities, including atrial arrhythmias and atrial fibrillation. Researchers continue to work on integrating PPG sensing capabilities with wearable devices, such as AI smartwatches, to develop ubiquitous health-monitoring solutions that extend beyond currently available wearable heart rate monitoring technologies [26].

Over the past five years, PPG has been actively integrated into smartwatches and fitness bracelets, not only for detecting pathologies but also for assessing the health status of healthy individuals. One study demonstrated that smartwatches equipped with PPG technology accurately measure heart rate and show a high correlation with ECG recordings for heart rate and R-R intervals in at-risk patients ($r = 0.891$). These findings suggest that such devices may be useful for continuous monitoring of patients with CVD [26; 27].

A recent study by Chinese researchers (2025) reported that among PPG parameters, SDNN and rMSSD were independent predictors of major adverse cardiovascular events (hereinafter – MACE). The study found that lower SDNN and rMSSD values were associated with a higher risk of adverse outcomes ($p < 0.05$). These findings confirm that both parameters, including rMSSD, are important not only for assessing cardiovascular function but also for prognostic risk stratification [28].

Several studies have shown that in patients with arterial hypertension and coronary heart disease, PPG-derived parameters, specifically SDNN (standard deviation of NN intervals) and RMSSD (root mean square of successive interval differences), reliably reflect autonomic regulation. A reduction in these indices correlates with increased risk of cardiovascular complications and higher mortality ($r = 0.9$, $p < 0.05$) [29; 30].

Features of cardiovascular regulation and arterial stiffness in CVD based on the results of photoplethysmographic analysis

The term “vascular aging” refers to age-related changes in blood vessels, such as reduced elasticity, which can reduce the efficiency of the vascular system. Arterial stiffness, resulting from arterial elasticity loss, is an important indicator of vascular aging. Understanding the relationship between vascular aging and arterial stiffness contributes to a better understanding of age-related diseases, including coronary heart disease, diabetes, heart failure, and atherosclerosis [31; 32].

Currently, the PPG method is increasingly used to assess arterial stiffness for early screening of coronary heart disease and arrhythmia risk. This optical technology measures changes in blood volume within tissue microvascular beds by detecting variations in light absorption. The PPG signal is considered a promising tool for evaluating vascular age and can be applied in both clinical and consumer devices. The morphology and temporal parameters of the PPG pulse wave reflect physiological vascular aging, alterations in arterial stiffness, changes in blood pressure, and the development of atherosclerosis. Consequently, numerous methods have been developed to estimate vascular age based on PPG analysis [32-34].

International researchers, including Redjan Ferizoli and colleagues, assessed arterial stiffness by applying a feature-extraction method to PPG signals and analyzed their relevance to CVS in vitro to identify morphological features associated with increased vascular stiffness. In their study, artificial vessels were created to simulate various stages of healthy and diseased arteries. Using PPG, distinct morphological changes were recorded that correlated with arterial stiffness parameters. The results demonstrated that PPG signals exhibited the greatest changes in amplitude-related characteristics, while infrared parameters reflecting pulse width were more closely associated with alterations in arterial stiffness [35].

The COVID-19 pandemic has significantly influenced research directions and outcomes, including studies on arterial stiffness assessment. Recent studies indicate that individuals who have recovered from COVID-19 show notable differences in vascular function compared to those without a history of infection. Arterial stiffness was also found to be higher in men than in women ($p < 0.001$). A recent PPG-based study demonstrated that patients with hypertension who had recovered from COVID-19 exhibited significantly higher heart rates compared to hypertensive patients without a history of COVID-19 ($p < 0.001$). These findings suggest that the increased incidence of CVD may also be, in part, a consequence of the SARS-CoV-2 pandemic, which lasted from 2019 to 2023 [36; 37].

Vallée et al. identified the additional prognostic value of arterial stiffness in assessing the risk of developing atherosclerotic CVD. They demonstrated a nonlinear relationship between arterial stiffness levels and the 10-year CVD risk, as calculated using a pooled cohort equation model ($p < 0.001$). These findings further confirm that increased arterial stiffness is associated with a higher risk of cardiovascular complications. Analysis of the PPG signal allows not only the assessment of long-term (10-year) risk but also the early detection of cardiovascular pathology [35; 38; 39].

Studies conducted by Dewig (2023) using Bayesian analysis and by Kantrowitz (2025) showed that the SDNN metric exhibits the greatest stability across measurement methods, whereas rMSSD demonstrates lower equivalence between pulse rate variability and HRV metrics. This difference may significantly influence the interpretation of their relationship with arterial stiffness parameters [40]. Additional technical and clinical studies conducted between 2023 and 2025 (Zieff, 2023; Hellqvist, 2024-2025; Vargas, 2025) assessed pulse wave velocity and pulse wave characteristics using PPG and wearable devices. The results of these studies have substantially contributed to understanding the limitations in accuracy, reproducibility, and scalability of PPG-based methods, which are critical for their clinical application and integration into personalized cardiovascular health monitoring technologies [41-43].

The prognostic role of PPG and artificial intelligence in determining the risk of developing cardiovascular diseases

The introduction of AI has led to unprecedented advances in medicine, and these modern technologies have the potential to significantly improve the diagnosis, treatment, and prevention of many diseases. The development of medical AI is closely linked to advances in deep machine learning algorithms. For example, some studies have demonstrated remarkable success in establishing correlations between PPG parameters and various biological processes and systems. This integration has significantly facilitated progress in cardiovascular assessment [18;44-46].

Weng et al. (2023) developed a deep learning-based CVD risk score (DLS) to predict the risk of cardiovascular events using only age, gender, smoking status, and changes in PPG as risk factors. The results showed that the deep learning model provided statistically significant predictive information about CVD risk ($p < 0.05$) [18].

Machine learning algorithms can analyze large volumes of data and identify patterns associated with specific diseases. In a recent study, Abdullah S et al. developed a machine learning approach to assess hypertension stages using PPG. The developers developed three machine learning models (DT, LDA, and LSVM) for classifying CVDs. Results showed that the DT model achieved 96.87 % accuracy, LDA 84.37 %, and LSVM 93.75 % on the test dataset. Thus, integrating PPG with AI can serve as an informative digital biomarker for stratifying hypertension severity, with important clinical implications for assessing vascular risk and implementing early preventive measures to slow disease progression [44]. However, the study did not assess the models' ability to predict clinical outcomes such as cardiovascular morbidity or hypertension-related complications.

Bartels et al. (2024) reported on the feasibility of estimating age as a proxy for vascular aging using PPG signals obtained from smartphones during real-life user activity. The study highlights the potential of such approaches for scalable population screening and remote monitoring of vascular health. Nevertheless, the authors noted significant limitations related to signal quality variability, the presence of artifacts, and the need for more sophisticated adaptive filtering and data-cleaning methods to ensure reliable estimates [45].

Current research confirms that PPG and HRV can serve as informative digital biomarkers for assessing cardiovascular risk. The application of AI methods, including machine learning and deep learning, enables the integration of multiple PPG and HRV features with clinical data, enhancing patient stratification based on CVD risk. Recent studies (Nie et al., 2025; Weng et al., 2023; Abdullah & Kristoffersson, 2023) highlight the high potential of these approaches for predicting vascular aging, arterial stiffness, and hypertension severity [44; 45].

The integration of AI with PPG and HRV parameters represents a promising tool for cardiovascular risk prediction. However, standardization, external validation, improved data quality, and the development of interpretable models are necessary for clinical implementation. Future research should address existing methodological and clinical gaps to ensure that these digital biomarkers become reliable components of personalized medicine in cardiology [46].

Discussion

The articles analyzed demonstrate that PPG plays an important role in diagnosing CVD. Based on our literature review, we conclude that PPG signals may be a prognostic marker of CVD risk, as supported by studies conducted by Izabela Szoltysek-Boldys et al. in patients with hypertension and atherosclerosis. The study demonstrated that arterial stiffness, assessed by PPG signals, is an early indicator of CVD. Furthermore, PPG studies have proven useful for monitoring nighttime increases in blood pressure. With the widespread use of sleep tracking devices with embedded photoplethysmographic sensors, this approach may provide a means for large-scale assessment of nocturnal blood pressure fluctuations in individuals with normal blood pressure and, potentially, a tool for identifying individuals at risk for cardiovascular or cerebrovascular disease. This further demonstrates the prognostic value of PPG studies [36; 48].

Imaging methods for diagnosing CVD and vascular aging are expensive, often impractical, and require specialist involvement. Imaging techniques such as MRI and angiography must be performed in a hospital setting, where qualified specialists are available to acquire images and record data. This complicates the approach of outpatient patient monitoring. Therefore, a practical, specialist-independent, and relatively inexpensive diagnostic tool is crucial for continuous, real-time monitoring of vascular aging [49].

This literature review discusses the importance and practicality of PPG in medicine. PPG's ease of use enables long-term studies to determine whether prevention and treatment methods for CVD and vascular aging can alter arterial stiffness and HRV, and whether a PPG-based device can detect the risk of developing CVD.

However, the use of PPG to predict cardiovascular risk has some limitations, as arterial stiffness parameters measured by PPG depend on signal quality, which in turn depends on the patient's skin properties at the time of measurement, including individual skin texture, blood oxygen saturation, blood flow velocity, skin temperature, and measurement conditions. Therefore, the accuracy of heart rate extraction from the PPG signal, as well as the standardization of the resulting signals, remains an unresolved technical issue [50].

Despite PPG's long history, the physiological model of photoplethysmographic signal formation remains a subject of ongoing debate. In many studies, the potential of continuous monitoring of non-invasive signals, particularly the integration of FPG and ECG, is being investigated to improve the efficiency of early detection and diagnosis of heart failure. In this way, FPG analysis can be used in the future for the instant diagnosis of heart failure [51].

In this literature review, we discussed the importance of a deep learning model for estimating the age of AI-FPG to optimize the assessment of the CVS condition. This proves the generalizability of future research using FPG-signals with machine learning.

Conclusions

PPG is currently considered a promising non-invasive method for the early detection of cardiovascular disorders and assessment of cardiovascular risk. Analysis of PPG signals provides valuable information on vascular wall condition, arterial stiffness, HRV, and other functional parameters of CVS , enabling the early detection of subclinical changes.

Recent studies demonstrate the high efficiency of machine learning and deep learning methods for processing PPG and HRV signals. Integration with AI enhances CVD risk stratification, improves the accuracy of predicting vascular aging and hypertension stages, and opens new opportunities for personalized medicine.

In long-term studies, the predictive performance of PPG remains limited due to fewer protocols, high device-compatibility variation, and insufficient clinical trials. Most existing studies are cross-sectional, limited, or the cohorts lack inclusivity.

To increase the clinical relevance of PPG, large, long-term prospective studies are needed. Standardizing methods for PPG and HRV signal acquisition and processing, along with developing interpretable and robust AI models, is essential. Future research should focus on improving the accuracy of measuring PPG parameters, such as HRV, SDNN, RMSSD, and LF/HF, across physical and daily activities, and on integrating PPG parameters with other biomarkers to assess CVDs.

The combination of PPG with modern AI technologies plays a key role in the early and accurate diagnosis of vascular aging, assessing arterial stiffness, and cardiovascular risk stratification. The planned assessment may play a critical role in prevention strategies and early intervention in cardiovascular disease management.

References

1. Roth G. A., Mensah G. A., Johnson C. O., Addolorato G., Ammirati E. Global burden of cardiovascular diseases and risk factors, 1990-2019: update from the GBD 2019 study // Journal of the American College of Cardiology. – 2019. – Vol. 76(25). – P. 2982-3021. – DOI: 10.1016/j.jacc.2020.11.010.
2. Preisner K., Hetjens S. Risk factors and preventive measures for cardiovascular diseases // Journal of Clinical Medicine. – 2024. – Vol. 13. – Article No. 3308. – DOI: 10.3390/jcm13113308.
3. Karimpour P., May J. M., Kyriacou P. A. Photoplethysmography for the assessment of arterial stiffness // Sensors. – 2023. – Vol. 23. – Article No. 9882. – DOI: 10.3390/s23249882.
4. Visseren F. L. J., Mach F., Smulders Y. M. et.al. 2021 ESC guidelines on cardiovascular disease prevention in clinical practice // European Heart Journal. – 2021. – Vol. 42(34). – P. 3227–3337. – DOI: 10.1093/eurheartj/ehab484.
5. Shaffer F., Ginsberg J. P. An overview of heart rate variability metrics and norms // Frontiers in Public Health. – 2017. – Vol. 5. – Article No. 258. – DOI: 10.3389/fpubh.2017.00258.
6. Chatterjee S., Budidha K., Kyriacou P. A. Investigating the origin of photoplethysmography using a multiwavelength Monte Carlo model // Physiological Measurement. – 2020. – Vol. 41(8). – Article No. 084001. – DOI: 10.1088/1361-6579/aba008.
7. Schäfer A., Vagedes J. How accurate is pulse rate variability as an estimate of heart rate variability? A review on studies comparing photoplethysmographic technology with an electrocardiogram // International Journal of Cardiology. – 2013. – Vol. 166(1). – P. 15-29. – DOI: 10.1016/j.ijcard.2012.03.119.
8. Adriana Camargo Oliveira, Pedro Miguel Guimarães Marques Cunha. Vascular Aging and Arterial Stiffness // Arq Bras Cardiol. – 2022. – Vol. 119(4). – 604-615. – DOI: https://doi.org/10.36660/abc.20210708.
9. Global Burden of Cardiovascular Diseases and Risks 2023 Collaborators. Global, regional, and national burden of cardiovascular diseases and risk factors in 204 countries and territories, 1990–2023 // Journal of the American College of Cardiology. – 2025. – Vol. 86(22). – P. 2167-2243. – DOI: 10.1016/j.jacc.2025.08.015.

10. Ungvari Z., Tarantini S., Sorond F., Merkely B., Csiszar A. Mechanisms of vascular aging: a geroscience perspective: JACC focus seminar // Journal of the American College of Cardiology. – 2020. – Vol. 75(8). – P. 931-941. – DOI: 10.1016/j.jacc.2019.11.061.
11. Aminuddin A., Rusanuar N. D., Md Lazim M. R., Ugusman A., Abd Rahman I. Z., Chellappan K., Mohamad M. S. F. Markers of vascular function and future coronary artery disease risk among Malaysians with individual cardiovascular risk factors // Biomedicines. – 2025. – Vol. 13(4). – P. 899. – DOI: 10.3390/biomedicines13040899.
12. Lapitan, D. G., Tarasov, A. P., Shtyflyuk, M. E., & Rogatkin, D. A. (2024). On the Origin of the Photoplethysmography Signal: Modeling of Volumetric and Aggregation Effects. Photonics, 11(7), 637. https://doi.org/10.3390/photonics11070637
13. Charlton P. H., Allen J., Bailón R. et.al. The 2023 wearable photoplethysmography roadmap // Physiological Measurement. – 2023. – Vol. 44(11). – Article No. 111001. – DOI: 10.1088/1361-6579/acead2.
14. Selvaraj N., Jaryal A., Santhosh J., Deepak K. K., Anand S. Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography // Journal of Medical Engineering & Technology. – 2008. – Vol. 32(6). – P. 479-484. – DOI: 10.1080/03091900701781317.
15. Park J., Seok H. S., Kim S.-S., Shin H. Photoplethysmogram analysis and applications: an integrative review // Frontiers in Physiology. – 2022. – Vol. 12. – Article No. 808451. – DOI: 10.3389/fphys.2021.808451.
16. Jayadevappa B. M., Holi M. S. Photoplethysmography: design, development, analysis and applications in clinical and physiological measurement: a review // International Journal of Innovative Research in Science, Engineering and Technology. – 2016. – Vol. 5(3). – DOI: 10.15680/IJIRSET.2016.0503145.
17. Moraes J. L., Rocha M. X., Vasconcelos G. G. Advances in photoplethysmography signal analysis for biomedical applications // Sensors. – 2018. – Vol. 18. – Article No. 1894. – DOI: 10.3390/s18061894.
18. Kiselev A. R., Karavaev A. S. The intensity of oscillations of the photoplethysmographic waveform variability at frequencies 0.04–0.4 Hz as an effective marker of hypertension and coronary artery disease in males // Blood Pressure. – 2020. – Vol. 29(1). – P. 55-62. – DOI: 10.1080/08037051.2019.1645586.
19. Weng W. H., Baur S., Daswani M. et.al. Predicting cardiovascular disease risk using photoplethysmography and deep learning // PLOS Global Public Health. – 2024. – Vol. 4(6). – Article No. 0003204. – DOI: 10.1371/journal.pgph.0003204.
20. Kantrowitz A. B., Ben-David K., Morris M. et.al. Pulse rate variability is not the same as heart rate variability: findings from a large, diverse clinical population study // Frontiers in Physiology. – 2025. – Vol. 16. – Article No. 1630032. – DOI: 10.3389/fphys.2025.1630032.
21. Tiwari R., Kumar R., Malik S., Raj T., Kumar P. et.al. Analysis of heart rate variability and implication of different factors on heart rate variability // Current Cardiology Reviews. – 2021. – Vol. 17(5). – Article No. 160721189770. – DOI: 10.2174/1573403X16999201231203854.
22. Podolyan N. P., Mizeva I. A., Belaventseva A. V. Imaging photoplethysmography quantifies endothelial dysfunction in patients with risk factors for cardiovascular complications // Biomedical Signal Processing and Control. – 2023. – Vol. 86. – Article No. 105168. – DOI: 10.1016/j.bspc.2023.105168.
23. Маршутин Н. А. Вариабельность сердечного ритма у больных с хронической сердечной недостаточностью при изменении преднагрузки // Новая наука: теоретический и практический взгляд. – 2017. – Т. 1, № 3. – С. 5-8.
24. Ikonomidis I., Makavos G., Lekakis J. Arterial stiffness and coronary artery disease // Current Opinion in Cardiology. – 2015. – Vol. 30(4). – P. 422-431. – DOI: 10.1097/HCO.0000000000000179.
25. Zekavat S. M., Aragam K., Emdin C. et.al. Genetic association of finger photoplethysmography-derived arterial stiffness index with blood pressure and coronary artery disease // Arteriosclerosis, Thrombosis, and Vascular Biology. – 2019. – Vol. 39(6). – P. 1253-1261. – DOI: 10.1161/ATVBAHA.119.312626.
26. Борисенко Т. Л. Клиническое значение нелинейных параметров вариабельности сердечного ритма у пациентов с сердечно-сосудистыми заболеваниями // Журнал Гродненского государственного медицинского университета. – 2020. – Т. 18, № 3. – С. 223-229. – DOI: 10.25298/2221-

8785-2020-18-3-223-229.
27. Blok S., Piek M. A., Tulevski I. I. The accuracy of heartbeat detection using photoplethysmography technology in cardiac patients // Journal of Electrocardiology. – 2021. – Vol. 67. – P. 148-157. – DOI: 10.1016/j.jelectrocard.2021.06.013.
28. Men, L., Chen, B., Yang, L., et al. (2025). Heart rate variability's value in predicting out-of-hospital major adverse cardiovascular events in patients with chronic heart failure. Cardiovascular Therapeutics, Article 6412775. DOI: https://doi.org/10.1155/cdr/6412775.
29. Mironov S. A., Kiselev A. R., Simonyan M. A. et.al. Low-frequency skin microvascular oscillations: dynamics, synchronization and compliance with changes in vascular tone during the tilt test // Saratov Journal of Medical Scientific Research. – 2019. – Vol. 15(3). – P. 783-790.
30. Brozat M., Böckelmann I., Sammito S. Systematic review on HRV reference values // Journal of Cardiovascular Development and Disease. – 2025. – Vol. 12. – Article No. 214. – DOI: 10.3390/jcdd12060214.
31. Con J. C., Lampi M. C., Reinhart-King C. A. Aging-induced vascular stiffening: causes and consequences // Frontiers in Genetics. – 2015. – Vol. 6. – Article No. 112. – DOI: 10.3389/fgene.2015.00112.
32. Kim K. B., Baek H. J. Photoplethysmography in wearable devices: a comprehensive review of technological advances, current challenges, and future directions // Electronics. – 2023. – Vol. 12. – Article No. 2923. – DOI: 10.3390/electronics12132923.
33. Charlton P. H., Paliakaitė B., Pilt K. et.al. Assessing hemodynamics from the photoplethysmogram to gain insights into vascular age: a review from VascAgeNet // American Journal of Physiology – Heart and Circulatory Physiology. – 2022. – Vol. 322(4). – P. 493-522. – DOI: 10.1152/ajpheart.00392.2021.
34. Vasan R. S., Pan S., Larson M. G., Mitchell G. F., Xanthakis V. Arteriosclerosis, atherosclerosis, and cardiovascular health: joint relations to the incidence of cardiovascular disease // Hypertension. – 2021. – Vol. 78. – P. 1232-1240.
35. Ferizoli R., Karimpour P., May J. M., Kyriacou P. A. Arterial stiffness assessment using PPG feature extraction and significance testing in an in vitro cardiovascular system // Scientific Reports. – 2024. – Vol. 14, № 1. – Article No. 2024. – DOI: 10.1038/s41598-024-51395-y.
36. Szołtysek-Bołdys I., Zielińska-Danch W., Łoboda D. et.al. Do photoplethysmographic parameters of arterial stiffness differ depending on the presence of arterial hypertension and/or atherosclerosis? // Sensors. – 2024. – Vol. 24. – Article No. 4572. – DOI: 10.3390/s24144572.
37. Podrug M., Koren P., Dražić Maras E. и др. Long-term adverse effects of mild COVID-19 disease on arterial stiffness, and systemic and central hemodynamics: a pre–post study // Journal of Clinical Medicine. – 2023. – Vol. 12. – Article No. 2123. – DOI: 10.3390/jcm12062123.
38. Vallée A. Added value of arterial stiffness index for the 10-year atherosclerotic cardiovascular disease risk determination in a middle-aged population-based study // Clinical Research in Cardiology. – 2023. – Vol. 112(11). – P. 1679-1689.
39. Chen H., Fan F., Ye Z. et.al. Photoplethysmography-derived arterial stiffness index delivered greater cardiovascular prevention value to non-elderly: a retrospective cohort study based on UK Biobank // Journal of Clinical Hypertension. – 2025. – Vol. 27(5). – Article No. 70058. – DOI: 10.1111/jch.70058.
40. Dewig H. G., Cohen J. N. et.al. Electrocardiogram and photoplethysmogram-based heart rate variability are not equivalent: a Bayesian simulation analysis: preprint // medRxiv. – 2023. – DOI: 10.1101/2023.08.24.23294449.
41. Zieff S. et.al. Pulse-wave velocity assessments derived from a simple photoplethysmography device: agreement with a referent device // Frontiers in Cardiovascular Medicine. – 2023. – DOI: 10.3389/fcvm.2023.1108219.
42. Vargas J. M., Bahloul M. A., Boularas M. M. и др. Assessment of pulse wave velocity through weighted visibility graph metrics from photoplethysmographic signals // Scientific Reports. – 2025. – Vol. 15. – Article No. 31325. – DOI: 10.1038/s41598-025-16598-x.
43. Hellqvist H., Karlsson M., Hoffman J., Kahan T., Spaak J. Estimation of aortic stiffness by finger photoplethysmography using enhanced pulse wave analysis and machine learning // Frontiers in Cardiovascular Medicine. – 2024. – Vol. 11. – Article No. 1350726. – DOI: 10.3389/fcvm.2024.1350726.
44. Abdullah S., Kristoffersson A. Machine learning approaches for cardiovascular hypertension stage

estimation using photoplethysmography and clinical features // Frontiers in Cardiovascular Medicine. – 2023. – Vol. 10. – Article No. 1285066. – DOI: 10.3389/fcvm.2023.1285066.
45. Barthels M., Gruwez H., De Cooman T., Duncker D., Vandervoort P. Predicting age from real-world smartphone-acquired PPG // Proceedings of Computing in Cardiology (CinC). – 2024.
46. Nie G., Zhao Q., Tang G. и др. Artificial intelligence-derived photoplethysmography age as a digital biomarker for cardiovascular health // arXiv. – 2025. – Preprint.
47. Yilmaz G., Lyu X., Ong J. L., Ling L. H., Penzel T., Yeo B. T. T., Chee M. W. L. Nocturnal blood pressure estimation from sleep plethysmography using machine learning // Sensors (Basel). – 2023. – Vol. 23(18). – Article No. 7931. – DOI: 10.3390/s23187931.
48. Victor O. A., Chen Y., Ding X. Non-invasive heart failure evaluation using machine learning algorithms // Sensors (Basel). – 2024. – Vol. 24(7). – Article No. 2248. – DOI: 10.3390/s24072248.
49. Raisi-Estabragh Z., Szabo L., Schuermans A., Salih A. M., Chin C. W. L., Vágó H., Altmann A., Ng F. S., Garg P., Pavanello S., Marwick T. H., Petersen S. E. Non-invasive techniques for tracking biological aging of the cardiovascular system: JACC family series // JACC: Cardiovascular Imaging. – 2024. – Vol. 17(5). – P. 533-551. – DOI: 10.1016/j.jcmg.2024.03.001.
50. Allen J. Photoplethysmography and its application in clinical physiological measurement // Physiological Measurement. – 2007. – Vol. 28(3). – P. 1-39. – DOI: 10.1088/0967-3334/28/3/R01.
51. Baldoumas G., Peschos D., Tatsis G., Chronopoulos S. K., Christofilakis V., Kostarakis P., Varotsos P., Sarlis N. V., Skordas E. S., Bechlioulis A. et al. A prototype photoplethysmography electronic device that distinguishes congestive heart failure from healthy individuals by applying natural time analysis // Electronics. – 2019. – Vol. 8(11). – Article No. 1288. – DOI: 10.3390/electronics8111288.

References

1. Roth, G. A., Mensah, G. A., Johnson, C. O., Addolorato, G., & Ammirati, E. (2020). Global burden of cardiovascular diseases and risk factors, 1990-2019: Update from the GBD 2019 study. Journal of the American College of Cardiology, 76(25), 2982-3021. DOI: https://doi.org/10.1016/j.jacc.2020.11.010.
2. Preisner, K., & Hetjens, S. (2024). Risk factors and preventive measures for cardiovascular diseases. Journal of Clinical Medicine, 13, 3308. DOI: https://doi.org/10.3390/jcm13113308.
3. Karimpour, P., May, J. M., & Kyriacou, P. A. (2023). Photoplethysmography for the assessment of arterial stiffness. Sensors, 23, 9882. DOI: https://doi.org/10.3390/s23249882.
4. Visseren, F. L. J., Mach, F., Smulders, Y. M., et al. (2021). 2021 ESC guidelines on cardiovascular disease prevention in clinical practice. European Heart Journal, 42(34), 3227-3337. DOI: https://doi.org/10.1093/eurheartj/ehab484.
5. Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. Frontiers in Public Health, 5, 258. DOI: https://doi.org/10.3389/fpubh.2017.00258.
6. Chatterjee, S., Budidha, K., & Kyriacou, P. A. (2020). Investigating the origin of photoplethysmography using a multiwavelength Monte Carlo model. Physiological Measurement, 41(8), 084001. DOI: https://doi.org/10.1088/1361-6579/aba008.
7. Schäfer, A., & Vagedes, J. (2013). How accurate is pulse rate variability as an estimate of heart rate variability? A review on studies comparing photoplethysmographic technology with an electrocardiogram. International Journal of Cardiology, 166(1), 15-29. DOI: https://doi.org/10.1016/j.ijcard.2012.03.119.
8. Oliveira, A. C., & Cunha, P. M. G. M. (2022). Vascular aging and arterial stiffness. Arquivos Brasileiros de Cardiologia, 119(4), 604-615. DOI: https://doi.org/10.36660/abc.20210708.
9. Global Burden of Cardiovascular Diseases and Risks 2023 Collaborators. (2025). Global, regional, and national burden of cardiovascular diseases and risk factors in 204 countries and territories, 1990-2023. Journal of the American College of Cardiology, 86(22), 2167-2243. DOI: https://doi.org/10.1016/j.jacc.2025.08.015.
10. Ungvari, Z., Tarantini, S., Sorond, F., Merkely, B., & Csiszar, A. (2020). Mechanisms of vascular aging: A geroscience perspective: JACC focus seminar. Journal of the American College of Cardiology, 75(8), 931-941. DOI: https://doi.org/10.1016/j.jacc.2019.11.061.
11. Aminuddin, A., Rusanuar, N. D., Md Lazim, M.

R., Ugusman, A., Abd Rahman, I. Z., Chellappan, K., & Mohamad, M. S. F. (2025). Markers of vascular function and future coronary artery disease risk among Malaysians with individual cardiovascular risk factors. Biomedicines, 13(4), 899. DOI: https://doi.org/10.3390/biomedicines13040899.

12. Lapitan, D. G., Tarasov, A. P., Shtyflyuk, M. E., & Rogatkin, D. A. (2024). On the origin of the photoplethysmography signal: Modeling of volumetric and aggregation effects. Photonics, 11(7), 637. DOI: https://doi.org/10.3390/photonics11070637.

13. Charlton, P. H., Allen, J., Bailón, R., et al. (2023). The 2023 wearable photoplethysmography roadmap. Physiological Measurement, 44(11), 111001. DOI: https://doi.org/10.1088/1361-6579/acead2.

14. Selvaraj, N., Jaryal, A., Santhosh, J., Deepak, K. K., & Anand, S. (2008). Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography. Journal of Medical Engineering & Technology, 32(6), 479-484. DOI: https://doi.org/10.1080/03091900701781317.

15. Park, J., Seok, H. S., Kim, S.-S., & Shin, H. (2022). Photoplethysmogram analysis and applications: An integrative review. Frontiers in Physiology, 12, 808451. DOI: https://doi.org/10.3389/fphys.2021.808451.

16. Jayadevappa, B. M., & Holi, M. S. (2016). Photoplethysmography: Design, development, analysis and applications in clinical and physiological measurement: A review. International Journal of Innovative Research in Science, Engineering and Technology, 5(3). DOI: https://doi.org/10.15680/IJIRSET.2016.0503145.

17. Moraes, J. L., Rocha, M. X., & Vasconcelos, G. G. (2018). Advances in photoplethysmography signal analysis for biomedical applications. Sensors, 18, 1894. DOI: https://doi.org/10.3390/s18061894.

18. Kiselev, A. R., & Karavaev, A. S. (2020). The intensity of oscillations of the photoplethysmographic waveform variability at frequencies 0.04-0.4 Hz as an effective marker of hypertension and coronary artery disease in males. Blood Pressure, 29(1), 55-62. DOI: https://doi.org/10.1080/08037051.2019.1645586.

19. Weng, W. H., Baur, S., Daswani, M., et al. (2024). Predicting cardiovascular disease risk using photoplethysmography and deep learning. PLOS Global Public Health, 4(6), e0003204. DOI: https://doi.org/10.1371/journal.pgph.0003204.

20. Kantrowitz, A. B., Ben-David, K., Morris, M., et al. (2025). Pulse rate variability is not the same as heart rate variability: Findings from a large, diverse clinical population study. Frontiers in Physiology, 16, 1630032. DOI: https://doi.org/10.3389/fphys.2025.1630032.

21. Tiwari, R., Kumar, R., Malik, S., Raj, T., & Kumar, P. (2021). Analysis of heart rate variability and implication of different factors on heart rate variability. Current Cardiology Reviews, 17(5), 160721189770. DOI: https://doi.org/10.2174/1573403X16999201231203854.

22. Podolyan, N. P., Mizeva, I. A., & Belaventseva, A. V. (2023). Imaging photoplethysmography quantifies endothelial dysfunction in patients with risk factors for cardiovascular complications. Biomedical Signal Processing and Control, 86, 105168. DOI: https://doi.org/10.1016/j.bspc.2023.105168.

23. Marshutin, N. A. (2017). Heart rate variability in patients with chronic heart failure during preload changes. New Science: Theoretical and Practical View, 1(3), 5-8. (In Russian).

24. Ikonomidis, I., Makavos, G., & Lekakis, J. (2015). Arterial stiffness and coronary artery disease. Current Opinion in Cardiology, 30(4), 422-431. DOI: https://doi.org/10.1097/HCO.0000000000000179.

25. Zekavat, S. M., Aragam, K., Emdin, C., et al. (2019). Genetic association of finger photoplethysmography-derived arterial stiffness index with blood pressure and coronary artery disease. Arteriosclerosis, Thrombosis, and Vascular Biology, 39(6), 1253-1261. DOI: https://doi.org/10.1161/ATVBAHA.119.312626.

26. Borisenko, T. L. (2020). Clinical significance of nonlinear heart rate variability parameters in patients with cardiovascular diseases. Journal of the Grodno State Medical University, 18(3), 223-229. DOI: https://doi.org/10.25298/2221-8785-2020-18-3-223-229 (In Russian).

27. Blok, S., Piek, M. A., & Tulevski, I. I. (2021). The accuracy of heartbeat detection using photoplethysmography technology in cardiac patients. Journal of Electrocardiology, 67, 148-157. DOI: https://doi.org/10.1016/j.jelectrocard.2021.06.013.

28. Men, L., Chen, B., Yang, L., et al. (2025).

Heart rate variability's value in predicting out-of-hospital major adverse cardiovascular events in patients with chronic heart failure. Cardiovascular Therapeutics, 6412775. DOI: https://doi.org/10.1155/cdr/6412775.

29. Mironov, S. A., Kiselev, A. R., Simonyan, M. A., et al. (2019). Low-frequency skin microvascular oscillations: Dynamics, synchronization and compliance with changes in vascular tone during the tilt test. Saratov Journal of Medical Scientific Research, 15(3), 783-790.

30. Brozat, M., Böckelmann, I., & Sammito, S. (2025). Systematic review on HRV reference values. Journal of Cardiovascular Development and Disease, 12, 214. DOI: https://doi.org/10.3390/jcdd12060214.

31. Con, J. C., Lampi, M. C., & Reinhart-King, C. A. (2015). Aging-induced vascular stiffening: Causes and consequences. Frontiers in Genetics, 6, 112. DOI: https://doi.org/10.3389/fgene.2015.00112.

32. Kim, K. B., & Baek, H. J. (2023). Photoplethysmography in wearable devices: A comprehensive review of technological advances, current challenges, and future directions. Electronics, 12, 2923. DOI: https://doi.org/10.3390/electronics12132923.

33. Charlton, P. H., Paliakaitė, B., Pilt, K., et al. (2022). Assessing hemodynamics from the photoplethysmogram to gain insights into vascular age: A review from VascAgeNet. American Journal of Physiology – Heart and Circulatory Physiology, 322(4), 493-522. DOI: https://doi.org/10.1152/ajpheart.00392.2021.

34. Vasan, R. S., Pan, S., Larson, M. G., Mitchell, G. F., & Xanthakis, V. (2021). Arteriosclerosis, atherosclerosis, and cardiovascular health: Joint relations to the incidence of cardiovascular disease. Hypertension, 78, 1232-1240.

35. Ferizoli, R., Karimpour, P., May, J. M., & Kyriacou, P. A. (2024). Arterial stiffness assessment using PPG feature extraction and significance testing in an in vitro cardiovascular system. Scientific Reports, 14(1), 2024. DOI: https://doi.org/10.1038/s41598-024-51395-y.

36. Szołtysek-Bołdys, I., Zielińska-Danch, W., Łoboda, D., et al. (2024). Do photoplethysmographic parameters of arterial stiffness differ depending on the presence of arterial hypertension and/or atherosclerosis? Sensors, 24, 4572. DOI: https://doi.org/10.3390/s24144572.

37. Podrug, M., Koren, P., Dražić Maras, E., et al. (2023). Long-term adverse effects of mild COVID-19 disease on arterial stiffness, and systemic and central hemodynamics: A pre-post study. Journal of Clinical Medicine, 12, 2123. DOI: https://doi.org/10.3390/jcm12062123.

38. Vallée, A. (2023). Added value of arterial stiffness index for the 10-year atherosclerotic cardiovascular disease risk determination in a middle-aged population-based study. Clinical Research in Cardiology, 112(11), 1679-1689.

39. Chen, H., Fan, F., Ye, Z., et al. (2025). Photoplethysmography-derived arterial stiffness index delivered greater cardiovascular prevention value to non-elderly: A retrospective cohort study based on UK Biobank. Journal of Clinical Hypertension, 27(5), 70058. DOI: https://doi.org/10.1111/jch.70058.

40. Dewig, H. G., Cohen, J. N., et al. (2023). Electrocardiogram- and photoplethysmogram-based heart rate variability are not equivalent: A Bayesian simulation analysis. medRxiv. DOI: https://doi.org/10.1101/2023.08.24.23294449.

41. Zieff, S., et al. (2023). Pulse-wave velocity assessments derived from a simple photoplethysmography device: Agreement with a referent device. Frontiers in Cardiovascular Medicine. DOI: https://doi.org/10.3389/fcvm.2023.1108219.

42. Vargas, J. M., Bahloul, M. A., Boularas, M. M., et al. (2025). Assessment of pulse wave velocity through weighted visibility graph metrics from photoplethysmographic signals. Scientific Reports, 15, 31325. DOI: https://doi.org/10.1038/s41598-025-16598-x.

43. Hellqvist, H., Karlsson, M., Hoffman, J., Kahan, T., & Spaak, J. (2024). Estimation of aortic stiffness by finger photoplethysmography using enhanced pulse wave analysis and machine learning. Frontiers in Cardiovascular Medicine, 11, 1350726. DOI: https://doi.org/10.3389/fcvm.2024.1350726.

44. Abdullah, S., & Kristoffersson, A. (2023). Machine learning approaches for cardiovascular hypertension stage estimation using photoplethysmography and clinical features. Frontiers in Cardiovascular Medicine, 10, 1285066. DOI: https://doi.org/10.3389/fcvm.2023.1285066.

45. Barthels, M., Gruwez, H., De Cooman, T., Duncker, D., & Vandervoort, P. (2024). Predicting age from real-world smartphone-acquired PPG.

Proceedings of Computing in Cardiology (CinC).
46. Nie, G., Zhao, Q., Tang, G., et al. (2025). Artificial intelligence-derived photoplethysmography age as a digital biomarker for cardiovascular health. arXiv (Preprint).
47. Yilmaz, G., Lyu, X., Ong, J. L., Ling, L. H., Penzel, T., Yeo, B. T. T., & Chee, M. W. L. (2023). Nocturnal blood pressure estimation from sleep plethysmography using machine learning. Sensors, 23(18), 7931. DOI: https://doi.org/10.3390/s23187931.
48. Victor, O. A., Chen, Y., & Ding, X. (2024). Non-invasive heart failure evaluation using machine learning algorithms. Sensors, 24(7), 2248. DOI: https://doi.org/10.3390/s24072248.
49. Raisi-Estabragh, Z., Szabo, L., Schuermans, A., Salih, A. M., Chin, C. W. L., Vágó, H., Altmann, A., Ng, F. S., Garg, P., Pavanello, S., Marwick, T. H., & Petersen, S. E. (2024). Non-invasive techniques for tracking biological aging of the cardiovascular system: JACC family series. JACC: Cardiovascular Imaging, 17(5), 533-551. DOI: https://doi.org/10.1016/j.jcmg.2024.03.001.
50. Allen, J. (2007). Photoplethysmography and its application in clinical physiological measurement. Physiological Measurement, 28(3), 1-39. DOI: https://doi.org/10.1088/0967-3334/28/3/R01.
51. Baldoumas, G., Peschos, D., Tatsis, G., Chronopoulos, S. K., Christofilakis, V., Kostarakis, P., Varotsos, P., Sarlis, N. V., Skordas, E. S., & Bechlioulis, A. (2019). A prototype photoplethysmography electronic device that distinguishes congestive heart failure from healthy individuals by applying natural time analysis. Electronics, 8(11), 1288. DOI: https://doi.org/10.3390/electronics8111288.

ЖҮРЕК-ҚАНТАМЫР АУРУЛАРЫНЫҢ ҚАУІПІН АНЫҚТАУДА ФОТОПЛЕТИЗМОГРАФИЯНЫ КЛИНИКАЛЫҚ ҚОЛДАНУ

Б. А. Бугибаева*[1], А. С. Абзалиева[2], Б. К. Абзалиев[2], М. Т. Абдирова[1], У. М. Сулейменова[2], А. М. Датқабаева[3]
[1] Қазақстан медициналық университеті «ҚДСЖМ», Қазақстан, Алматы
[2] Әл-Фараби атындағы Қазақ ұлттық университеті, Қазақстан, Алматы
[3] Е. А. Бөкетов атындағы Қарағанды ұлттық зерттеу университеті, Қазақстан, Қарағанды
Корреспондент автор

Аңдатпа

Кіріспе. Бұл әдеби шолу фотоплетизмография мен жүрек соғу ырғағының вариабельділігін қолдана отырып, жүрек-қан тамырлары қаупін бағалаудың заманауи әдістеріне арналған. Тамыр қабырғасының жағдайын, артериялардың қаттылығын, жүрек соғу жиілігін және микроциркуляцияны талдаудың инвазивті емес тәсілдері, сондай-ақ олардың жүрек-қантамырлары қауіп факторларымен байланысы қарастырылады.

Мақсаты: Фотоплетизмографияның жүрек-қантамырлары қаупін ерте анықтаудың инвазивті емес әдісі ретіндегі мүмкіндігін талдау және оны клиникалық тәжірибеде кеңінен қолдану қажеттілігін негіздеу.

*Материалдар мен әдістер***:** PubMed, Google Scholar, Cochrane кітапханасы, Scopus Preview, eLibrary және Cyberleninka дерекқорларында жүрек соғу ырғағының вариабельділігін және фотоплетизмографияны бағалау әдістері бойынша халықаралық және отандық дереккөздер ізделді. Іздеу кезеңі соңғы 10 жылды қамтыды.

Нәтижелер және талқылау: Шолу фотоплетизмография мен жүрек соғу ырғағының вариабельділігінің субклиникалық тамырлық өзгерістерді көрсетуге және жүрек-қантамырлары оқиғаларын болжауға қабілетті ақпараттық сандық маркерлер ретінде мүмкіндігін көрсетті. Дегенмен, шолу барысында шектеулер де анықталды: стандартталған сигнал жазу хаттамаларының жоқтығы, деректер сапасының өзгергіштігі, ұзақ мерзімді клиникалық нәтижелердің болмауы және модельдердің сыртқы валидациясының шектеулілігі. Ұсынылған деректер жүрек-қантамырларының денсаулығын кешенді бағалау үшін әрі қарай перспективалық зерттеулер жүргізу, сигнал сапасын жақсарту, түсіндірілетін жасанды интеллект модельдерін әзірлеу және фотоплетизмография/жүрек соғу ырғағының вариабельділігінің басқа биомаркерлермен біріктіру қажеттілігін растайды.

Қорытынды: Бұл әдеби шолу фотоплетизмографияның ерте жүрек-қан тамырларын бағалау үшін перспективалы және қолжетімді инвазивті емес әдіс екенін көрсетеді. Фотоплетизмография сигналдарын талдау артериялық қаттылықты, тамыр тонусын және жүрек-қан тамырлары қаупімен байланысты басқа да ерте субклиникалық өзгерістерді анықтауға мүмкіндік береді. Дегенмен, жоғары әлеуетіне қарамастан, әдістің клиникалық қолданылуы стандартталған хаттамалардың жоқтығы, құрылғылардың гетерогенділігі, деректер сапасының өзгергіштігі, клиникалық валидацияның жеткіліксіздігі және ұзақ мерзімді нәтижелері жоқ көлденең қима зерттеулердің басымдығымен шектеледі.

Түйін сөздер: *фотоплетизмография, жүрек ырғағының вариабелділігі, артериялық қаттылық, жүрек-қан тамырлары қаупі, жасанды интеллект, сандық биомаркерлер.*

КЛИНИЧЕСКОЙ ПРИМЕНЕНИЕ ФОТОПЛЕТИЗМОГРАФИИ ДЛЯ ВЫЯВЛЕНИЯ РИСКА РАЗВИТИЯ СЕРДЕЧНО-СОСУДИСТЫХ ЗАБОЛЕВАНИЙ

Б. А. Бугибаева*[1], А. С. Абзалиева[2], Б. К. Абзалиев[2], М. Т. Абдирова[1], У. М. Сулейменова[2], А. М. Даткабаева[3]

[1] Казахстанский медицинский университет «ВШОЗ», Казахстан, Алматы

[2] Казахский национальный университет имени Аль-Фараби, Казахстан, Алматы

[3] Карагандинский национальный исследовательский университет имени Е.А. Букетова, Казахстан, Караганда

**Корреспондирующий автор*

Аннотация

Введение. Настоящий литературный обзор посвящён современным методам оценки сердечно-сосудистого риска с использованием фотоплетизмографии и вариабельности сердечного ритма. Рассмотрены неинвазивные подходы к анализу состояния сосудистой стенки, артериальной жесткости, сердечного ритма и микроциркуляции, а также их связь с факторами риска сердечно-сосудистых заболеваний.

Цель. Проанализировать возможности фотоплетизмографии как неинвазивного метода раннего выявления риска сердечно-сосудистых заболеваний и обосновать необходимость её более активного применения в клинической практике.

Материалы и методы. Проведен поиск зарубежных и отечественных источников в базах данных PubMed, Google Scholar, Cochrane Library, Scopus Preview и eLibrary, CyberLeninka. посвященных методам оценки показателей вариабельности сердечного ритма и фотоплетизмографии. Глубина поиска составила 10 лет.

Результаты и обсуждение. Обзор выявил перспективность фотоплетизмографии и вариабельности сердечного ритма как информативных цифровых маркеров, способных отражать субклинические сосудистые изменения и предсказывать кардиоваскулярные события, при этом подчеркнуты существующие ограничения: необходимость стандартизации протоколов записи сигналов, вариабельность качества данных, отсутствие долгосрочных клинических исходов и ограниченная внешняя валидация моделей. Представленные данные подтверждают необходимость дальнейших проспективных исследований, улучшения качества сигналов, разработки интерпретируемых AI-моделей и интеграции фотоплетизмографии/вариабельности сердечного ритма с другими биомаркерами для комплексной оценки сердечно-сосудистого здоровья.

Выводы. Литературный обзор показывает, что фотоплетизмография является перспективным и доступным неинвазивным методом ранней оценки сердечно-сосудистого состояния. Анализ Фотоплетизмографии-сигналов позволяет выявлять артериальную жёсткость, сосудистый тонус и другие ранние субклинические изменения, связанные с риском сердечно-сосудистых заболеваний. Однако, несмотря на высокий потенциал, клиническое применение метода ограничено отсутствием стандартизированных протоколов, разнородностью устройств, вариабельностью качества данных и недостаточной клинической валидацией, а также преобладанием кросс-секционных исследований без долгосрочных исходов.

Ключевые слова: *фотоплетизмография, вариабельность сердечного ритма, артериальная жесткость, сердечно-сосудистый риск, искусственный интеллект, цифровые биомаркеры.*

АВТОРЛАР ТУРАЛЫ

Бугибаева Акбота – медицина ғылымдарының магистрі, «Медицина» білім беру бағдарламасының докторанты, Қазақстан медициналық университеті «Қоғамдық денсаулық сақтау жоғары мектебі», Қазақстан, Алматы; e-mail: akbotabugibaeva1988@gmail.com;ORCID: https://orcid.org/0000-0003-1417-2711.

Абзалиева Сымбат – медицина ғылымдарының кандидаты / PhD, Әл-Фараби атындағы Қазақ ұлттық университеті Ақпараттық технологиялар факультеті «Жасанды интеллект және Big Data» кафедрасының міндетін атқарушы доценті, Қазақстан, Алматы; e-mail: abzaliyeva.symbat@gmail.com; ORCID: https://orcid.org/0009-0004-9802-0129.

Абзалиев Қуат – медицина ғылымдарының докторы, Әл-Фараби атындағы Қазақ ұлттық университеті Ақпараттық технологиялар факультеті «Жасанды интеллект және Big Data» кафедрасының қауымдастырылған профессоры, Қазақстан, Алматы; e-mail: abzaliev_kuat@mail.ru; ORCID: https://orcid.org/0000-0003-2452-854X.

Абдирова Тамара – PhD докторы, Қазақстан медициналық университеті «Қоғамдық денсаулық сақтау жоғары мектебі», Қазақстан, Алматы; e-mail: t_abdirova@mail.ru;ORCID: https://orcid.org/0009-0004-9193-9378.

Сулейменова Мадина – медицина ғылымдарының магистрі, Әл-Фараби атындағы Қазақ ұлттық университетінің докторанты, Қазақстан, Алматы; e-mail: madekin940@gmail.com; ORCID: https://orcid.org/0009-0003-8553-5353.

Датқабаева Мөлдір – медицина ғылымдарының магистрі, Е.А. Бөкетов атындағы Қарағанды ұлттық зерттеу университетінің оқытушысы, Қазақстан, Қарағанды; e-mail: datkabaeva.moldir@bk.ru; ORCID: https://orcid.org/0009-0000-3693-185X.

ОБ АВТОРАХ

Бугибаева Акбота – магистр медицинских наук, докторант образовательной программы «Медицина» Казахстанского медицинского университета «Высшая школа общественного здравоохранения» Казахстан, Алматы; e-mail:akbotabugibaeva1988@gmail.com; ORCID: https://orcid.org/0000-0003-1417-2711.

Абзалиева Сымбат – кандидат медицинских наук / PhD, исполняющий обязанности доцента кафедры «Искусственный интеллект и Big Data» Факультета информационных технологий НАО «Казахский национальный университет имени Аль-Фараби» Казахстан, Алматы; e-mail: abzaliyeva.symbat@gmail.com; ORCID: https://orcid.org/0009-0004-9802-0129.

Абзалиев Куат – д.м.н. ассоциированный профессор кафедры «Искусственный интеллект и Big Data» Факультета информационных технологий НАО «Казахский национальный университет имени Аль-Фараби» Казахстан, Алматы; e-mail: abzaliev_kuat@mail.ru; ORCID: https://orcid.org/0000-0003-2452-854X.

Абдирова Тамара – доктор PhD, Казахстанский медицинский университет «Высшая школа общественного здравоохранения» Казахстан, Алматы; e-mail: t_abdirova@mail.ru; ORCID: https://orcid.org/0009-0004-9193-9378.

Сулейменова Мадина – магистр медицинских наук, докторант НАО «КазНУ им аль-Фараби» Казахстан, Алматы; e-mail: madekin940@gmail.com; ORCID: https://orcid.org/0009-0003-8553-5353.

Даткабаева Молдир магистр медицинских наук, преподователь Карагандинский национальный исследовательский университет имени Е.А. Букетова, Казахстан, Караганда; e-mail: datkabaeva.moldir@bk.ru; ORCID: https://orcid.org/0009-0000-3693-185X .

ABOUT AUTHORS

Bugibayeva Akbota – Master of Medical Sciences, PhD student of the educational program «Medicine» at Kazakhstan Medical University «Higher School of Public Health», Kazakhstan, Almaty; e-mail: akbotabugibaeva1988@gmail.com; ORCID: https://orcid.org/0000-0003-1417-2711.
Abzaliyeva Symbat – Candidate of Medical Sciences / PhD, Acting Associate Professor of the Department of «Artificial Intelligence and Big Data», Faculty of Information Technologies, Al-Farabi Kazakh National University, Kazakhstan, Almaty; e-mail: abzaliyeva.symbat@gmail.com; ORCID: https://orcid.org/0009-0004-9802-0129.
Abzaliyev Kuat – Doctor of Medical Sciences, Associate Professor of the Department of «Artificial Intelligence and Big Data», Faculty of Information Technologies, Al-Farabi Kazakh National University, Kazakhstan, Almaty; e-mail: abzaliev_kuat@mail.ru; ORCID: https://orcid.org/0000-0003-2452-854X.
Abdirova Tamara – PhD, Kazakhstan Medical University «Higher School of Public Health», Kazakhstan, Almaty; e-mail: t_abdirova@mail.ru; ORCID: https://orcid.org/0009-0004-9193-9378.
Suleimenova Madina – Master of Medical Sciences, PhD student at Al-Farabi Kazakh National University, Kazakhstan, Almaty; e-mail: madekin940@gmail.com; ORCID: https://orcid.org/0009-0003-8553-5353.
Datkabayeva Moldir – Master of Medical Sciences, Lecturer at E.A. Buketov Karaganda National Research University, Kazakhstan, Karaganda; e-mail: datkabaeva.moldir@bk.ru; ORCID: https://orcid.org/0009-0000-3693-185X.

Author contributions. *Conceptualization: Bugibayeva B.A.; Methodology: Bugibayeva B.A., Abzaliyeva A.S.; Data collection: Bugibayeva B.A.; Writing – review and editing: all authors; Supervision: Abzaliyeva A.S., Abzaliyev B.K., Datkabayeva A.M. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.*
Funding. *This study was conducted within the framework of a research project funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan (No. AP19677754, «Development of markers and a diagnostic algorithm for the detection and prevention of early cardiovascular aging»).*
Conflict of interest. *The authors declare that they have no competing interests that could have influenced the work reported in this paper.*
All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Article received: 22.09.2025year.
Accepted for publication:28.11.2025 year.