Analysis of Pulse Wave Morphology Measured by Photoplethysmography During Arm Position Changes

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Abstract. Numerous studies underscore the importance of analyzing pulse wave morphology via photoplethysmography (PPG) as an accessible method for investigating localized vascular responses. Contemporary approaches to modeling pulse wave morphology are based on the assumption that the dicrotic wave arises from reflections at vascular bifurcations and other vascular inhomogeneities. An alternative perspective posits that normal blood circulation is sustained through smooth muscle tone. To validate this hypothesis, we analyzed pulse wave morphology during arm position changes, which are associated with alterations in arterial tone within the vascular system. This study substantiates the feasibility of evaluating vascular resistance changes through dicrotic wave curvature during arm repositioning, measurable via the slope angle of the PPG signal at this segment. Furthermore, it is shown that the venulo-arteriolar reflex triggered by arm position changes leads to ambiguous dynamics in pulse wave amplitude variations. The presence or absence of the venulo-arteriolar reflex impacts pulse wave amplitude but does not affect dicrotic wave curvature, which is exclusively governed by changes in arteriolar smooth muscle tone.

Keywords: pulse wave morphology; photoplethysmography; diastolic wave; dicrotic wave; venulo-arteriolar reflex; vascular resistance.

Paper #9263 received 7 Apr 2025; revised manuscript received 29 May 2025; accepted for publication 18 Jun 2025; published online 28 Jun 2025. doi: 10.18287/JBPE25.11.020310.

1 Introduction

The pulse wave morphology carries information about vascular atherosclerosis, arterial hypertension, diabetes mellitus [1–3], and endothelial dysfunction, which serves as a predictor of cardiovascular disease risk [4]. Greatest interest lies in studying pulse wave morphology using non-invasive methods such as rheography, photoplethysmography (PPG), and sphygmography. Key parameters include: the ratio of systolic to diastolic peak amplitudes, the area under the pulse wave curve, the ratio of areas before and after the dicrotic wave, the ratio of pulse wave width to systolic amplitude, the amplitude of the reflected wave (augmentation index), and others [5]. Currently, photoplethysmography (PPG), as a simple and accessible method, is widely used for developing diagnostic approaches to assess the cardiovascular system. The PPG signal is divided into pulsatile and non-pulsatile components [6, 7]. The pulsatile component of the PPG signal consists of a systolic phase (anacrotic phase), corresponding to increased blood volume in the microcirculatory bed due to cardiac ejection, and a diastolic phase (catacrotic phase), representing blood redistribution in the microcirculatory bed. The systolic peak is identified at the apex of the anacrotic phase, where systolic blood ejection is maximal. The minimum trough on the diastolic segment is defined as the dicrotic notch (incisura), and the subsequent peak is termed the dicrotic rise [8].

Numerous studies highlight PPG's utility as a cost-effective tool for analyzing localized vascular responses. However, localized pulse wave analysis for assessing specific arterial segments is not yet recommended, as such measurements lack validation in prospective studies for predicting cardiovascular disease (CVD) outcomes. This limitation has excluded

This paper was presented at the Saratov Fall Meeting 2024 – International Symposium on Optics and Biophotonics, Saratov, Russian Federation, September 24–24, 2024.

PPG and other pulse wave analysis methods from the Russian Ministry of Health's clinical guideline classification system.

Modern model concepts of pressure pulse wave formation [9] and proportional changes in PPG signal amplitude [10] are based on the theory of reflected wave existence [5]. However, there is currently no consensus on the mechanism of reflected wave formation. Specifically, modern textbooks and monographs state that "the secondary dicrotic wave (rise) is caused by blood reflection from closed valves" [11–13]. This claim is no longer repeated in ultrasound diagnostics literature, as the dicrotic segment in Doppler ultrasound is identified as retrograde blood flow [14, 15].

A significant body of research assumes that the reflected wave originates from vascular bifurcations and other vascular inhomogeneities [16–20]. In Ref. [21], it is proposed to consider reflected wave formation as a combination of reflections from the ends of branching arterial networks. Identifying the exact site of reflected wave generation remains controversial. For example, it is argued that the most prominent reflection occurs at the bifurcation of the descending abdominal aorta [5]. If this is accepted, the reflected wave should propagate in the direction of systolic blood ejection into peripheral arm vessels, whereas Doppler ultrasound reveals retrograde flow.

With aging, the diastolic pulse wave morphology becomes smoother, and the dicrotic wave shifts toward the systolic peak. Blood flow dynamics in elderly subjects are influenced by at least two factors: increased stiffness of arterial vessel walls and reduced smooth muscle tone in arterioles. These factors explain age-related changes in pulse wave morphology: increased stiffness leads to earlier retrograde flow waves, while reduced smooth muscle tone diminishes dicrotic wave prominence.

A second debated issue involves the venulo-arteriolar reflex to explain the observed increase in PPG signal amplitude during arm elevation above heart level. Raising the arm reduces arterial and venous blood volume in the limb, as recorded by laser Doppler flowmetry, which measures both pulsatile and steady components [22].

Several studies note that reduced blood volume decreases PPG signal amplitude [20, 23–25]. For instance, Ref. [26] demonstrated through anesthesia, sympathetic activation, and vasoconstrictor studies that peripheral vasodilation increases systolic peak amplitude, while vasoconstriction reduces it. Thus, arm elevation and reduced blood volume should decrease pulse wave amplitude. However, the inverse trend observed in Refs. [20, 27, 28] is attributed to the venulo-arteriolar reflex. As shown below, this pattern is not universal. Despite complex explanations, authors consistently emphasize the need for further research on this reflex.

Despite ambiguity in the reflected wave mechanism, pulse wave morphology remains widely used for vascular disease diagnostics. An alternative perspective posits that normal blood circulation is maintained by smooth muscle tone. To validate this, we propose analyzing pulse wave morphology during arm repositioning, which directly alters arterial vascular tone. We also discuss the venulo-arteriolar reflex during positional changes, demonstrating that PPG amplitude variations are not universally consistent.

2 Materials and Methods

The study was conducted on a group of volunteers comprising 10 relatively healthy young males aged 21–28 years. Exclusion criteria included tobacco smoking, arterial hypertension, other cardiovascular diseases (CVDs), diabetes mellitus, acute respiratory viral infections (ARVIs), and the use of vasoactive medications.

The experiment was performed in a room maintained at 23 ± 1 °C, with participants in a seated position. Prior to blood flow signal recording, participants remained seated for at least 5 min with their arm resting on a horizontal support at heart level. For each subject, three sequential recordings were performed with the right arm (equipped with the PPG sensor) in different positions:

1. Baseline recording (middle arm position): the arm rested relaxed and flexed on a horizontal support at heart level.
2. Lower arm position recording: the arm hung freely downward.
3. Upper arm position recording: the hand rested on a horizontal support to minimize muscular strain.

Arm repositioning took approximately 30–40 s, allowing PPG signal amplitude and morphology to stabilize. After a 10-s recording in the second (lower) position, the arm was moved to the third (upper) position by vertical elevation at the elbow joint. The total duration in the second position did not exceed one minute. The third PPG recording began after an additional 30–40 s.

This protocol was designed to study the vascular system's rapid response to gravity-induced blood flow changes. Additionally, prolonged arm positioning was avoided to optimize practicality for developing a screening procedure assessing vascular reactions to positional changes. A PPG device, Easy Pulse (v.1.0), was placed on the distal phalanx of the right middle finger. The device operates by detecting changes in blood volume within finger tissues using a 950 nm light source and a photodetector from the HRM-2511E sensor (Kyoto Electronic Co., China). Signal acquisition involved multiple stages. The photodetector signal was first passed through a passive high-pass RC filter to block the DC component of the PPG signal within the 0.5–10 Hz frequency range. Simultaneous low-pass filtering and amplification of the analog signal were performed using the MCP6004 operational amplifier. The amplified signal was then digitized by an NI ELVIS device (National Instruments, USA) and stored in the computer's persistent memory for subsequent processing.

3 PPG Signal Measurement and Processing Technique

Fig. 1 shows the PPG pulse wave of a 22-year-old volunteer recorded over 10 s with the arm positioned downward (−).

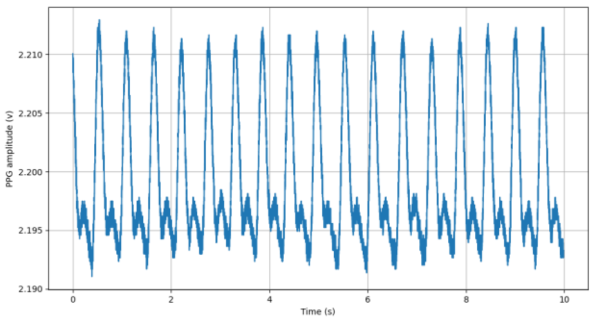

Fig. 1 PPG pulse wave of a 22-year-old volunteer with the arm positioned downward (−), recorded over 10 s.

Subsequent processing involved isolating cardiac cycles and normalizing pulse waves to unit amplitude (Fig. 2a). Unlike earlier methodologies, we selected the curvature of the diastolic segment on the dicrotic wave (specifically, the transition from the dicrotic notch [incisura] to the dicrotic peak) as the informative parameter.

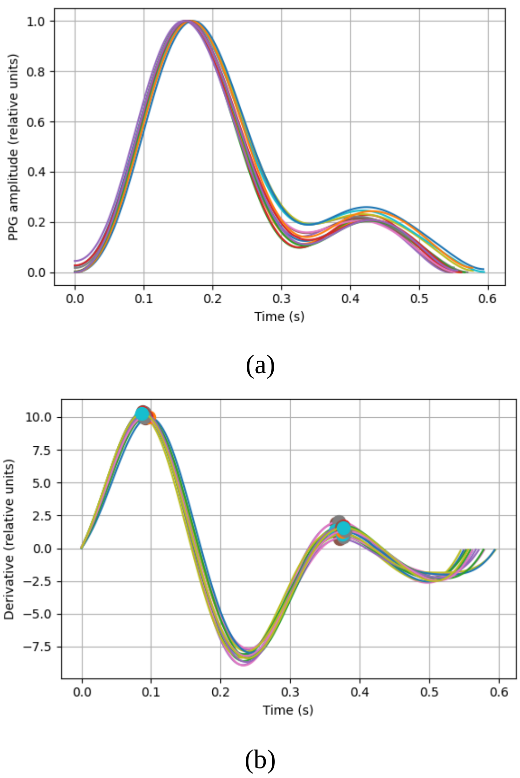

Fig. 2 Isolation of cardiac cycles, normalization of pulse waves to unit amplitude, and first derivative of the pulse wave: (a) normalized cardiac cycles of the PPG pulse wave; (b) corresponding derivative waveforms with maxima on the pulse wave.

To quantify dicrotic wave curvature, the first derivative was computed for each cardiac cycle (Fig. 2b). Colored circles mark derivative maxima corresponding to the transition from the incisura to the dicrotic peak.

Signal processing and analysis were performed using the Python programming language and Jupyter Notebook. Raw pulse wave signals were filtered with a 3rd-order Butterworth low-pass filter (passband: 0–6 Hz). Amplitude normalization scaled the signal to the [0, 1] range. Peak detection was performed using the *scipy.signal* library and the *argrelextrema* function, while derivatives were calculated using the *diff* method of the *numpy* library. The tangent of the slope angle (tanα) at the extremum point was computed, where α represents the maximum PPG slope angle during the incisura-to-dicrotic-peak transition.

Fig. 3 displays the variability of maximum PPG slope angles derived from dicrotic wave derivative maxima (Fig. 2b). This variability reflects spontaneous vascular tone regulation mechanisms.

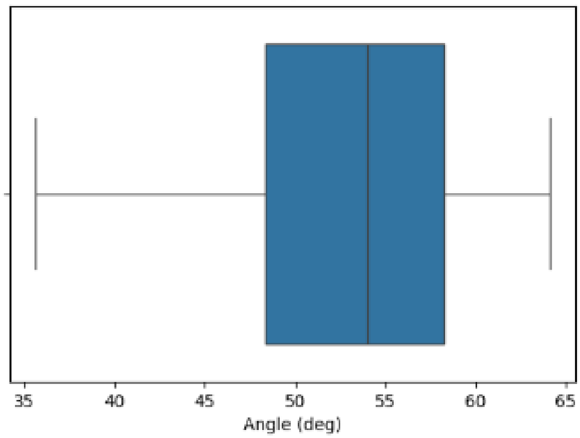

Fig. 3 Spread of derivative values in the dicrotic wave region for the pulse wave shown in Fig. 2.

PPG measurements were taken in seated participants under three arm positions: (−) below heart level (arm hanging vertically downward), (0) at heart level (arm resting freely on a table), (+) above heart level (arm elevated, supported at the elbow). These positions minimized myogenic influences from skeletal muscles on vascular walls [29].

Fig. 4 illustrates diastolic PPG segments (10-s recordings) and their corresponding derivative waveforms with dicrotic wave maxima. Averaged PPG amplitudes were: (a, b) 0.085 V (position −), (c, d) 0.038 V (position 0), (e, f) 0.018 V (position +). Maximum PPG slope angles, calculated from derivative peaks, averaged: (a, b) −16° (position −), (c, d) +27° (position 0), (e, f) +53° (position +).

As shown in Fig. 4, the mean dicrotic wave slope angle increases as the arm shifts from above (+) to below (−) heart level, ranging from −16° to +53°. Notably, the dicrotic wave region remained stationary relative to the systolic peak (anacrotic apex).

doi: 10.18287/JBPE25.11.020310

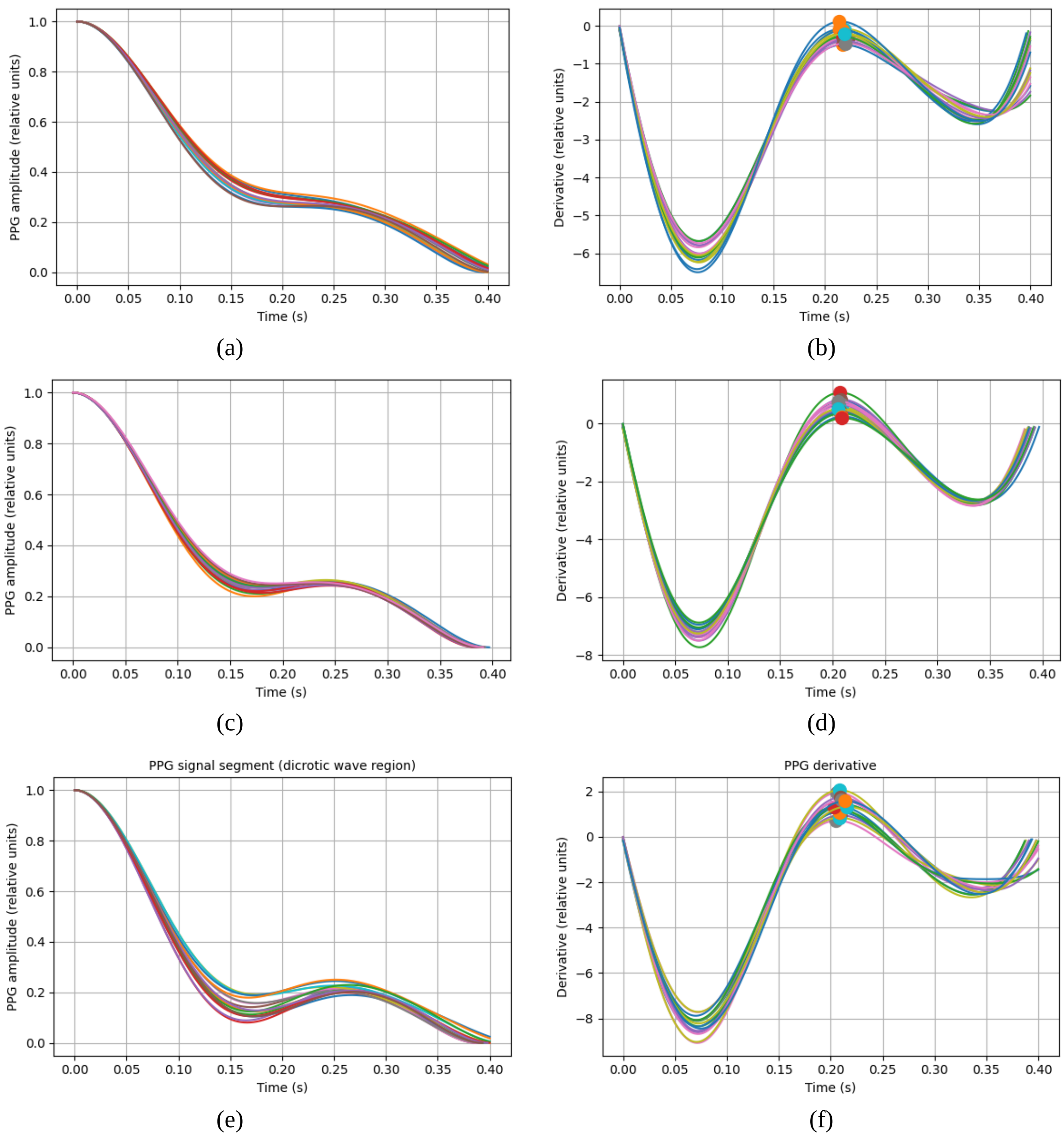

Fig. 4 (a, c, e) Normalized diastolic PPG segments (10-s recording) from a volunteer in three arm positions and (b, d, f) their corresponding derivative waveforms with maxima in the dicrotic wave region: (a, b) (+), (c, d) (0), (e, f) (−).

4 Results of the Study

Fig. 5 shows the calculated maximum PPG slope angles on the dicrotic wave segment for 10 volunteers across three arm positions: (−) below heart level, (0) at heart level, and (+) above heart level. Fig. 6 displays the spread of PPG slope angles for the same group. As seen in Figs. 5 and 6, lowering the arm from position (+) to (−) resulted in an increase in the dicrotic wave slope angle, corresponding to elevated arterial resistance.

Figs. 7 and 8 present the PPG signal amplitudes and their variability for 10 volunteers under the three arm positions: (+) above heart level, (0) at heart level, and (−) below heart level. Fig. 7 reveals that the relationship between PPG amplitude and arm position varies among individuals: amplitudes may increase, decrease, or peak at heart level. Fig. 8 demonstrates that, on average, the PPG amplitude peaks when the arm is positioned at heart level.

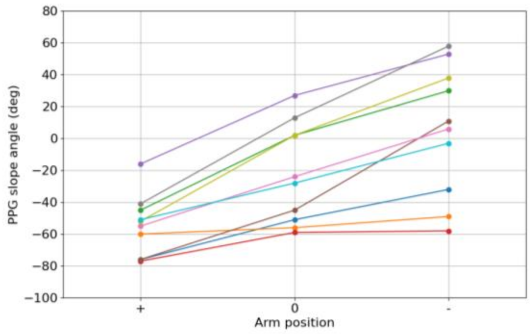

Fig. 5 PPG slope angle values on the dicrotic wave segment for 10 volunteers across three arm positions.

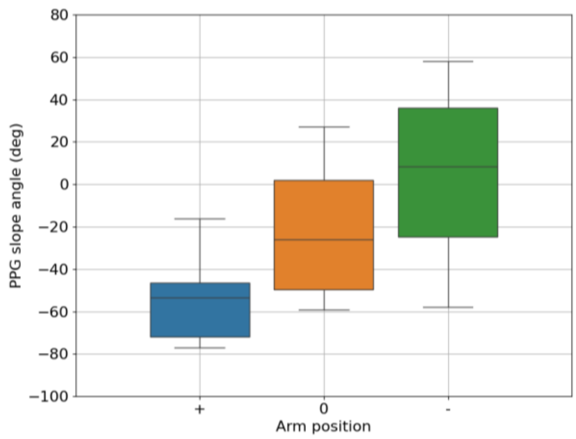

Fig. 6 Box-plot of spread of PPG slope angles on the dicrotic wave segment for 10 volunteers across three arm positions.

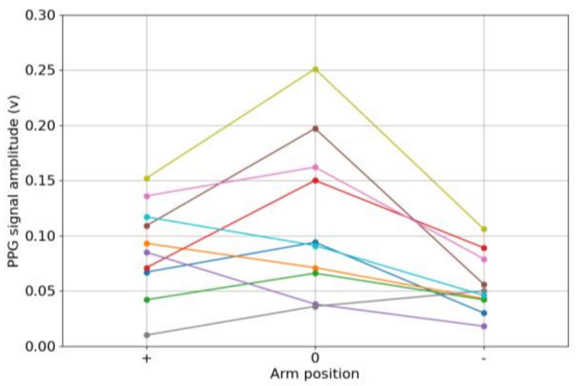

Fig. 7 PPG signal amplitude values for 10 volunteers across three arm positions.

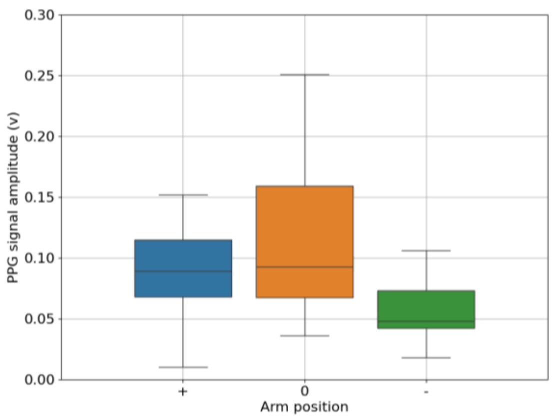

Fig. 8 Box-plot of PPG signal variability values for 10 volunteers across three arm positions.

This variability in PPG amplitude dependence on arm position aligns with existing literature and is likely associated with the type and state of the autonomic nervous system in individual volunteers. However, the autonomic nervous system's influence on PPG waveform morphology appears less pronounced, as the pattern of its change is more consistent and clearly defined.

5 Discussion

During arm repositioning, we measured changes in two parameters: systolic wave amplitude and pulse wave curvature at the dicrotic segment, calculated from the PPG slope angle at this segment. It has been shown that the dependence of systolic wave amplitude on arm position relative to heart level can exhibit various patterns: increasing, decreasing, or peaking at heart level (Fig. 8).

Most studies investigating pulse wave amplitude during arm repositioning describe a uniform trend: increased amplitude during arm elevation and decreased amplitude during lowering [20, 27, 28]. These studies utilized an extended, supported arm position and measurements were carried out 2–5 min or more minutes after repositioning. The age of the participants was usually over 30 years old. Observed perfusion changes were attributed to venous pressure variations and the venulo-arteriolar reflex.

The article by Z. Ovadia-Blechman et al. [29] reports a non-monotonic systolic amplitude dependence on arm position, consistent with the trends shown in Fig. 8.

Our prior work revealed that the venulo-arteriolar reflex's manifestation depends on age and duration of arm positioning [30]. This reflex is most pronounced in elderly individuals, whereas autonomic activity dominates in younger cohorts. These factors explain the variable systolic amplitude dependence on arm position: increasing, decreasing, or peaking at heart level (Fig. 8).

In our protocol, recordings began 30–40 s after repositioning, followed by a 10-s PPG acquisition. This design captured rapid vascular responses to gravity-induced hemodynamic shifts. Resting the arm on a table in a flexed position minimized muscular tension and venulo-arteriolar reflex interference. However, suppressing sympathetic activity in young participants proved impossible, as confirmed by behavioral observations. We did not account for height, weight, autonomic dysfunction, or baseline finger temperature − factors potentially influencing reflex dynamics and amplitude trends.

The second observed pattern involved altered arterial resistance shaping the dicrotic wave during arm repositioning. This study pioneers explaining pulse wave morphology dynamics via arteriolar smooth muscle tone changes in the microcirculatory bed, despite prior reports of dicrotic wave attenuation during positional shifts.

For instance, Ref. [20] (Fig. 6) illustrates pulse wave morphology changes during arm repositioning, concluding that elevated arm positions increase vascular resistance. This conclusion, drawn from empirical data across age groups, athletes, and functional tests [9, 20, 31–33], assumes unchanged arm positioning during measurements.

Abandoning the "reflected wave" concept and focusing on smooth muscle tone yields opposing conclusions. Elevated arms exhibit prolonged systolic rise and decay times [20]. Reduced blood volume delays arterial filling, while decreased pressure lowers resistive vessel tone. Retrograde flow during diastole is also delayed, widening the diastolic wave. As the dicrotic peak's timing remains stable ([20] and our results), its vertical rise increases the reflection index (RI) despite diminished retrograde flow.

Studies [20, 33] claim that "arterial and arteriolar resistance should not significantly affect PPG morphology during arm elevation, with venous resistance dominating over arterial". This contradicts Doppler ultrasound findings.

Dicrotic wave formation on the diastolic segment arises from retrograde flow, detectable via ultrasound Doppler [14, 15, 34]. Vascular resistance calculations rely on retrograde-to-antegrade flow ratios, with retrograde flow magnitude linked to smooth muscle tone [35, 36]. Thus, steeper systolic decay and dicrotic rise slopes correspond to increased resistance and arteriolar tone.

Arm repositioning alters vascular tone [22, 30, 37], modifying pulse wave curvature. The venulo-arteriolar reflex impacts amplitude but not dicrotic curvature, which is exclusively governed by arteriolar (not venular or anastomotic) smooth muscle tone [38, 39].

6 Conclusions

The functional test involving arm elevation or depression alters systolic wave amplitude and dicrotic wave curvature. We demonstrate that the dependence of systolic amplitude on arm position relative to heart level can vary: increasing, decreasing, or peaking at heart level. This hemodynamic variability may stem from age- and time-dependent manifestations of the venulo-arteriolar reflex.

In our study, blood flow signals in young volunteers were recorded 30–40 s after arm repositioning, followed by a 10-s PPG acquisition. Resting the flexed arm on a table at heart level minimized muscular tension and venulo-arteriolar reflex interference, though the reflex's presence/absence remained unconfirmed.

Numerous studies on diastolic pulse wave morphology highlight the lack of standardized PPG-based vascular assessment methods, leaving the mechanisms of incisura and dicrotic rise formation unclear.

Key evidence for reduced arterial tone during arm elevation lies in altered dicrotic wave morphology. We observed decreased dicrotic curvature and slope angle during arm elevation, with no significant shift in diastolic peak timing relative to the systolic peak.

Current pulse wave models assume systolic components arise from forward pressure waves propagating from the left ventricle to the periphery, while diastolic components originate from pressure waves reflected back from peripheral arterioles. The term "reflected wave" misrepresents retrograde flow dynamics and complicates interpretation. Our approach attributes dicrotic wave formation to arteriolar smooth muscle tone changes, which modulate retrograde flow and vascular resistance. Arm repositioning alters vascular filling, modifies arterial tone, and thereby adjusts retrograde flow magnitude and dicrotic curvature. The venulo-arteriolar reflex affects pulse wave amplitude but not dicrotic curvature, which is governed solely by arteriolar smooth muscle tone.

It should be noted that these conclusions are based on the results of a study of a group of young participants. In elderly patients, dicrotic curvature patterns may differ due to arteriolar wall stiffness and vascular pathologies (e.g., atherosclerosis, diabetes) [40].

Thus, both the amplitude and the morphology of the pulse wave on the dicrotic segment are essential components of photoplethysmogram analysis for diagnosing arterial vascular health and assessing changes in arterial resistance. When analyzing the pulse wave morphology on the diastolic segment, the arm's position relative to heart level must be accounted for.

Disclosures

All authors declare that there is no conflict of interest in this paper.

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