Doppler Ultrasound Indices of the Major Arteries as Markers of Vascular Tone during Thermal Stress

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Abstract. This study focuses on the effects of moderate thermal heating on microcirculation and peripheral hemodynamics, as well as on the interrelationship between changes detected by Laser Doppler Flowmetry (LDF) and Ultrasound Doppler (USD). Microcirculation and peripheral hemodynamics were evaluated in the context of cardiovascular diagnostics using LDF and USDG. LDF non-invasively assessed tissue perfusion, reflecting the state of arterioles, venules, precapillary sphincters, and capillaries, thereby evaluating blood filling and tone in the microcirculatory bed. USDG was employed to assess blood flow in major arteries and calculate peripheral resistance indices, including resistance and pulsatility indices. General thermal heating from 20°C to 30°C was applied to observe its impact on both microvascular tone and major artery resistance indices. Moderate thermal heating increased perfusion and amplified the amplitude of neurogenic and myogenic oscillation rhythms. Peripheral resistance, as determined by USDG, decreased with rising temperature. The retrograde blood flow component, indicative of the tone of distal muscular-type vessels, disappeared upon warming, suggesting reduced resistance in both major arteries and microvessels. Additionally, the amplitude of antegrade diastolic flow, associated with the properties of elastic-type arteries, increased. Changes in microcirculation and peripheral hemodynamics are interconnected and follow a common physiological pattern: vasodilation and reduced tone in the microcirculatory bed. The decrease in USDG spectral indices in major arteries during heating correlates directly with the reduction in microvascular tone. While USDG can detect vascular resistance changes within a single cardiac cycle, LDF requires significantly more time to register such changes in microvascular tone.

Keywords: vascular elasticity; vascular resistance; microcirculation; major artery; ultrasound Doppler; laser doppler flowmetry; thermal test.

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1 Introduction

Almost all major pathologies of the cardiovascular system are accompanied by significant impairments in microcirculation or blood flow in the major arteries. For the real-time assessment of microcirculation [1–3], Laser Doppler Flowmetry (LDF) is a promising method. To determine the hemodynamics of medium and small-caliber arteries and veins [4–6], Ultrasound Doppler (USDG) has proven to be highly effective. It is generally accepted that these methods provide information on the hemodynamic mechanisms of various functional systems in the body at the micro- and macrovascular levels. In the present work, we aim to demonstrate the relationship

between these methods for assessing hemodynamic changes during a general thermal functional test.

Studies using LDF [7–10] have established that both local and general thermal exposure induces a significant increase in cutaneous blood flow. The perfusion and the amplitude of blood flow oscillations in various frequency ranges are used to assess blood filling and tone in the microcirculatory bed. These oscillations are governed by active mechanisms of endothelial, neurogenic, and myogenic regulation [11–13].

Specifically, a study by Petrofsky et al. [7] demonstrated that exposure to air flows with different temperature parameters (38°C, 40°C, 42°C) for 20 min resulted in a significant increase in both skin blood flow and skin temperature. A similar increase in cutaneous blood flow was also observed in the works of Fedorovich and Skripal [14, 15].

An impaired microvascular response to thermal hyperemia is closely associated with increased cardiovascular mortality, underscoring the prognostic value of this non-invasive test for assessing skin microcirculatory function [16].

The investigation of regulatory mechanisms in microcirculation under various pathological conditions is made possible through the analysis of blood flow oscillation rhythms in tissues [17]. The microcirculatory response to local heating in both healthy individuals and patients with diabetes mellitus has been described in studies by Filina et al. [18] and Mizeva et al. [9]. It was found that a local increase in skin temperature from 25°C to 42°C leads to a significant rise in the microcirculation index, accompanied by a marked tendency for an increase in oscillation amplitude within the neurogenic and myogenic ranges. In patients with diabetes, a reduction in neurogenic vasodilation and an impairment of low-frequency vasomotions were noted, reflecting dysfunction in the autonomic regulation of vascular tone.

According to a study by Mallette et al. [12], passive heat stress significantly increases laser-Doppler flux relative to baseline levels. This is accompanied by an amplification of blood flow oscillations associated with nitric oxide-independent endothelial activity, as well as neurogenic, myogenic, respiratory, and cardiac rhythms. In contrast, oscillations reflecting nitric oxide-dependent endothelial activity showed no significant changes under the influence of passive heat stress.

A number of studies [19, 20] have shown that the indicator of oxidative metabolism of the NADH coenzyme can also be a marker of changes in the tone of the microcirculatory bed when heated. However, the dependence of this parameter, measured by modern LDF devices with integrated fluorescence analysis of blood flow [21], depends on the individual characteristics, the measuring zone, and even the phase of the menstrual cycle in women [20].

In contrast to LDF, the USDG method provides recording of the direction and velocity of blood flow in large arteries and veins, enabling the assessment of macrocirculatory blood flow and the calculation of spectral indices of peripheral resistance. For example, the Resistance Index (RI) serves as an integral indicator reflecting the total peripheral vascular resistance in the examined vascular bed. Within the classical approach, its calculation is based on the analysis of the direction and magnitude of blood flow during the diastolic phase of the cardiac cycle.

A study by Korkmaz et al. [22] demonstrated that the change in RI following reactive hyperemia of the brachial artery reflects the functional state of the endothelium and can be used in clinical practice as a diagnostic marker of vascular dysfunction. Furthermore, the RI level closely correlates with risk factors for coronary artery disease and serves as an indirect indicator of atherosclerotic changes. This is supported by data obtained from a group of renal transplant recipients, where an association was found between the renal RI and cardiovascular risk factors, as well as the thickening of the carotid intima-media complex – a marker of subclinical atherosclerosis [23].

The Pulsatility Index (PI) is an integral parameter reflecting a combination of peripheral resistance and stiffness (elasticity) of distal arteries, as well as the magnitude of cardiac output. It allows for the quantitative assessment of blood flow velocity over the cardiac cycle period [24].

The effect of local and whole-body heating on vascular function, including flow-mediated dilation and post-occlusive reactive hyperemia, has been comprehensively reviewed [25]. The authors demonstrated that systemic thermal exposure significantly increases forearm blood volume flow within the first minutes, which is accompanied by an increase in shear rate and enhanced antegrade flow, while a retrograde component is also present.

A review presented by Brothers et al. [26] analyzed data from a number of experimental studies investigating the impact of heat stress on dynamic cerebral autoregulation under conditions of significant blood pressure fluctuations. Based on the summarized results, the authors concluded that heat stress is accompanied by a reduction in systemic vascular resistance.

Acute thermal exposure exerts a pronounced effect on vascular regulation by enhancing endothelium-dependent vasodilation in conduit arteries. A study by Coombs et al. [27] analyzed the contribution of both skin temperature response and core body temperature to the flow-mediated dilation of the brachial artery during different modes of passive heating. During systemic thermal exposure without limb occlusion, a marked increase in antegrade blood flow velocity in the brachial artery was observed, accompanied by a progressive reduction of the retrograde component up to its complete disappearance.

Interest in studying limb blood flow obtained via ultrasound Doppler waveform is driven by the ability to visualize both antegrade and retrograde flow, which allows for the assessment of the functional state of the vascular system and the determination of its resistance. Results from a study by Thomas et al. [28] showed that leg immersion in hot water (42°C) for 30 min led to an increase in antegrade blood flow velocity and a decrease

in retrograde velocity. These changes were recorded in both the upper and lower limbs. The observed changes indicate the involvement of the resistive vascular bed in thermoregulatory mechanisms and the influence of the myogenic tone of small arteries and arterioles on peripheral circulation [29].

Literature analysis reveals studies that have investigated the vascular response to thermal exposure using either ultrasound Doppler or LDF. Simultaneous assessment of Doppler ultrasound blood flow indices and microcirculatory parameters could provide insights into the relationship between regulatory processes at the macro- and microcirculatory levels of the vascular system organization.

The aim of this work was to establish the possibility of using ultrasound Doppler ultrasound indices measured in the radial artery as a marker of microvascular tone during thermal stress.

2 Materials and Methods

2.1 Participants

Fifteen healthy volunteers (9 males and 6 females) with a mean age of 22 ± 2 years participated in this study. Prior to the experiment, each participant was thoroughly informed about the study's objectives, procedures, and methods, after which they provided written informed consent in accordance with the ethical standards for biomedical research. The study was approved by the Ethics Committee of the V.I. Razumovsky Saratov State Medical University (Protocol No. 9, April 4, 2023) and was conducted in a clinical setting under the supervision of medical personnel.

2.2 Microcirculation Assessment

Microcirculatory blood flow was assessed using the "LAZMA PF" device (LAZMA, Russia), which operates at a wavelength of 850 nm with a radiation power of 0.7 mW. The penetration depth of the laser beam into skin tissue was approximately 1.0–1.2 mm. The "LAZMA PF" probe was placed on the distal phalanx of the middle finger pad of the right hand. LDF signals were analyzed using Morlet wavelet transform, which decomposed the signals into frequency components of blood flow oscillations. Among the five existing frequency ranges, parameter changes were analyzed in only two: 0.02–0.06 Hz – neurogenic activity (blood flow regulation via sympathetic vascular innervation); 0.06–0.2 Hz – myogenic activity (contractions of vascular smooth muscle cells). This limitation is due to the duration of the LDF signals.

2.3 Ultrasound Doppler

Doppler waveforms were recorded using an "Edan U50" ultrasound system (Edan Instruments, China) with a 7.2 MHz transducer. Hemodynamic parameters were assessed using multiple modes: B-mode for visualization of vascular anatomy; color Doppler (CD) mapping for localization of arterial blood flow; and pulsed-wave Doppler (PW Doppler) for obtaining quantitative blood flow velocity parameters.

2.4 Study Protocol

The investigation was conducted in two phases. During the first phase, participants were seated in a laboratory room with a controlled temperature of 20 ± 1°C, monitored using a digital thermometer (Xiaomi Mijia Bluetooth Thermometer 2, China). Following a 15-min rest period for acclimatization, baseline measurements of microcirculation parameters were performed on the pad of the left index finger using LDF, along with recording Doppler waveforms of the radial artery using Doppler ultrasound.

In the second phase, participants moved to an adjacent room with an ambient temperature of 30 ± 1°C. After 15 min of whole-body thermal exposure, subsequent measurements of microcirculation were conducted on the pad of the distal phalanx of the left index finger (LDF) and Doppler waveforms of the radial artery (ultrasonography) were recorded while participants remained at rest.

2.5 Laser Doppler Flowmetry Parameters

The perfusion and amplitudes of blood flow oscillations in various frequency ranges were determined from LDF measurements. The perfusion (P) is defined as:

$$P = K \cdot N \cdot V_{avg}, \quad (1)$$

where K is the proportionality coefficient, N is the number of scatterers (erythrocytes) in the measured volume, and V_{avg} is their average velocity [30].

Since the LDF signal consists of slowly and rapidly varying components, the perfusion can be described as:

$$P(t) = Pc + \delta P(t), \quad (2)$$

where Pc represents the constant flow component and $\delta P(t)$ represents the variable flow component.

The constant component Pc reflects the average blood flow level in the microcirculatory bed over the selected observation period or LDF recording analysis interval. The variable component $\delta P(t)$ is determined by factors affecting blood flow stability – specifically, changes in the velocity V_{avg} and concentration N of erythrocytes in the measured volume.

The recorded amplitudes of neurogenic (An) and myogenic (Am) blood flow oscillations are directly related to microvascular lumen size and, consequently, to muscular tone. Neurogenic tone (NT) and myogenic tone (MT) of arterioles and resistive microvessels are related by the expressions [31]:

$$\mathrm{NT} = \frac{\sigma \cdot P_{avg}}{\mathrm{An} \cdot Pc}, \quad (3)$$

$$\mathrm{MT} = \frac{\sigma \cdot P_{avg}}{\mathrm{Am} \cdot Pc}, \quad (4)$$

where σ represents the standard deviation of the perfusion, and P_{avg} is the mean pressure in the peripheral vascular system.

A decrease in oscillation amplitude is associated with increased tone and stiffness of the vascular wall, while an increase in oscillation amplitude results from reduced vascular tone [31–33].

2.6 Ultrasound Doppler Parameters

The resistance index (RI) and pulsatility index (PI) were calculated from the ultrasound Doppler data, with averaging performed over three cardiac cycles. Typically, two different equations are used for calculating RI, accounting for peripheral vascular resistance [34]. The first equation is applied in cases of high vascular resistance with presence of retrograde blood flow:

$$\mathrm{RI}_{V_d} = \frac{V_{ps}+V_d}{V_{ps}}, \quad (5)$$

where V_{ps} is the peak systolic blood flow velocity and V_d is the peak retrograde blood flow velocity.

The second equation is used for cases of low vascular resistance:

$$\mathrm{RI}_{V_{ed}} = \frac{V_{ps}-V_{ed}}{V_{ps}}, \quad (6)$$

where V_{ed} represents the antegrade peak velocity.

It should be noted that in cases of low vascular resistance, the end-diastolic velocity V_{ed} is commonly used for calculating both RI and PI indices. However, in healthy young participants at room temperature, the end-diastolic velocity is typically zero due to high vascular resistance. Therefore, we employed modified formulas for calculating RI and PI indices, utilizing the diastolic velocity V_{ed} corresponding to the maximum antegrade flow. A similar approach was implemented in the monograph by Lelyuk, V.G. and Lelyuk, S.E. [34].

The expression for the PI for cases with high vascular resistance was determined from the following relationship:

$$\mathrm{RI}_{V_d} = \frac{V_{ps}+V_d}{\mathrm{TAMX}}, \quad (7)$$

where TAMX – the time-averaged maximum velocity as the mean value of all measured maximum blood flow velocities obtained at equal time points throughout one cardiac cycle:

$$\mathrm{TAMX} = \frac{\sum_{i=1}^{n} V_i}{n}, \quad (8)$$

where V_i is the measured value of maximum blood flow velocity in the i-th pixel (cm/s), and n is the number of measured points (pixels on the Doppler waveform) per cardiac cycle.

For cases with low vascular resistance, the PI was determined from the following relationship:

$$\mathrm{PI}_{V_{ed}} = \frac{V_{ps}-V_{ed}}{\mathrm{TAMX}}. \quad (9)$$

where V_{ed} was also defined as the antegrade peak diastolic velocity.

2.7 Statistical Analysis

Data analysis was performed using mathematical statistics methods. The STATISTICA 10 software package (StatSoft, Inc.) was used for data processing. Given the small sample size and non-normal distribution of data, the Wilcoxon T-test – one of the most powerful non-parametric analysis methods – was applied for comparing quantitative variables in two dependent samples. Parameter differences were considered statistically significant at $p \le 0.05$, indicating a high probability that the observed changes in blood flow parameters were not due to random factors.

3 Results

3.1 LDF Measurements of Microcirculatory Blood Flow

Figure 1 presents a graph illustrating changes in the perfusion, measured in perfusion units (p.u.), in a healthy 25-year-old subject under two conditions: in a room with air temperature of 20 ± 1°C and 30 ± 1°C, respectively.

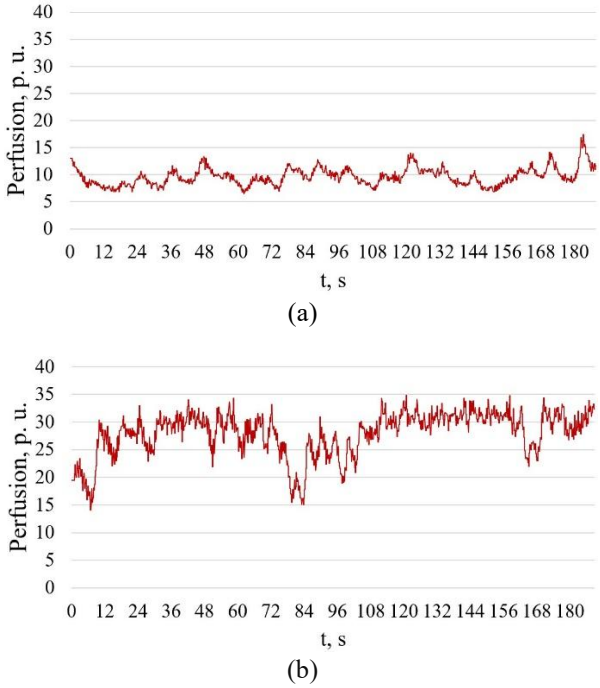


Fig. 1 Perfusion of a 25-year-old study participant: (a) in a room with air temperature of 20 ± 1°C, (b) in a room with air temperature of 30 ± 1°C.

As shown in Fig. 1, the average level of the perfusion in the volunteer before exposure to the warm room was 8 p.u., which corresponds to the baseline state of microcirculation under normal temperature conditions (20 ± 1°C). After moving to the room with elevated

temperature (30 ± 1°C), this parameter increased to 27.8 p.u.

Figure 2 presents diagrams showing changes in the perfusion for a group of 15 study participants under different temperature conditions.

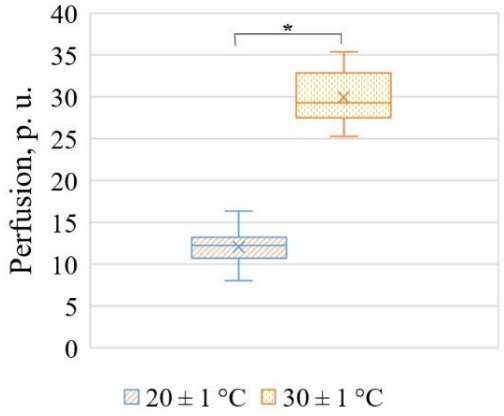


Fig. 2 Diagram of changes in the perfusion for a group of 15 study participants in rooms with air temperatures of 20 ± 1°C and 30 ± 1°C. *Significance of perfusion difference between the two conditions: $p = 0.0007$.

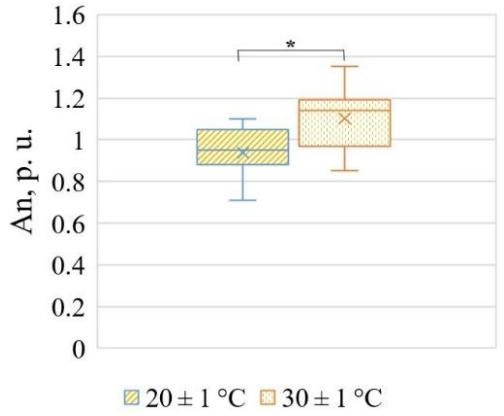


Fig. 3 Diagram of changes in the amplitude of neurogenic oscillations (An) of microcirculation in rooms with air temperatures of 20 ± 1°C and 30 ± 1°C. *Significance of difference in An values between the two conditions: $p = 0.0026$.

For study participants in the room with a temperature of 20 ± 1°C, the median value of the perfusion was 12.2 p.u.

Increasing the temperature to 30 ± 1°C led to a significant rise in the microcirculation index, which may indicate a physiological response of the body to external temperature changes. In the cooler environment (20 ± 1°C), the microcirculation level remained at a relatively low and stable state. Furthermore, under high temperature conditions, greater data variability was observed, potentially reflecting differences in individual responses of participants to the ambient temperature change. Statistical analysis confirmed that the difference in perfusion values between the 20 ± 1°C room temperature and the 30 ± 1°C elevated temperature conditions was statistically significant ($p = 0.0007$).

Of particular interest is the analysis of blood flow oscillations, whose rhythms reflect changes in vascular tone. Figure 3 presents diagrams showing changes in the amplitude of neurogenic blood flow oscillations for a group of 15 study participants under different temperature conditions.

Based on the conducted study, it can be concluded that exposure to elevated temperature induces a statistically significant ($p = 0.0026$) increase in the amplitude of neurogenic oscillations in the blood microcirculation system.

Figure 4 presents diagrams illustrating features of myogenic regulation in a group of 15 study participants under different temperature conditions.

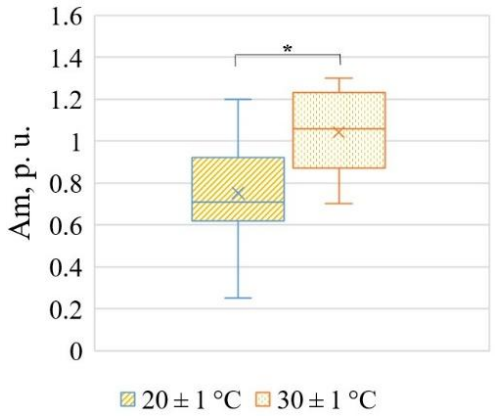


Fig. 4 Diagram of changes in the amplitude of myogenic oscillations (Am) of microcirculation in rooms with air temperatures of 20 ± 1 °C and 30 ± 1 °C. *Significance of difference in Am values between the two conditions: $p = 0.001$.

The data presented in Figure 4 show that at a temperature of 20 ± 1°C, the median value of the myogenic oscillation amplitude (Am) was 0.71 r.u. The interquartile range under these conditions varied from 0.62 to 0.92 r.u. The mean value was 0.74 r.u.

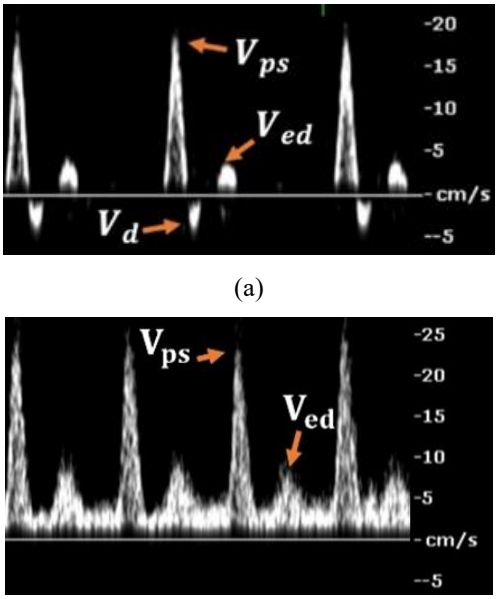
The data at 30 ± 1°C indicates a significant change in the amplitude of myogenic oscillations. The median amplitude value increased to 1.06 r.u., indicating a rise in myogenic activity with increasing temperature. The interquartile range widened, now spanning from 0.87 to 1.23 r.u., suggesting increased variability of the measurements compared to the 20°C condition.

The difference between the Am values under the 20 ± 1°C room temperature and the 30 ± 1°C elevated temperature conditions was statistically significant ($p = 0.001$).

3.2 Doppler Ultrasound Measurements of Major Artery Blood Flow

Figures 5a and 5b present an example of the hemodynamic response to thermal exposure typical for the entire subject group. The ultrasound Doppler waveforms of a 25-year-old study participant were

obtained while he was in rooms with air temperatures of 20 ± 1°C and 30 ± 1°C, respectively.



(a)

(b)

Fig. 5 Ultrasound spectral Doppler waveforms of a 25-year-old study participant showing peak velocities at different time points in the cardiac cycle. (a) in a room with an air temperature of 20 ± 1°C, (b) in a room with an air temperature of 30 ± 1°C.

At an air temperature of 20 ± 1 °C, according to Doppler ultrasound data, the peak systolic blood flow velocity (V_{ps}) was 18.5 cm/s, the retrograde blood flow (V_d) had a negative value (–3.5 cm/s), and the maximum antegrade blood flow velocity (V_{ed}) was 3.2 cm/s. Furthermore, the direction of antegrade flow remained positive throughout the entire measurement period.

Under air temperature conditions of 30 ± 1 °C, the most pronounced changes concerned the shape of the ultrasound Doppler waveforms. When participants were in the elevated temperature environment, all subjects exhibited alterations in hemodynamic parameters to varying degrees, specifically a significant increase in peak systolic velocity, a decrease in the peak retrograde flow value, and an increase in the peak antegrade flow value. These changes indicate alterations in vascular tone and redistribution of blood flow during thermal exposure.

When the ambient temperature increased to 30 ± 1°C, the study participant (Fig. 5b) showed an increase in peak systolic velocity to 24.3 cm/s. According to Doppler ultrasound data, retrograde blood flow (V_d) was absent, indicating a significant reduction in vascular resistance. The maximum antegrade blood flow velocity (V_{ed}) increased to 7.8 cm/s, while maintaining its positive direction, confirming the primary role of elastic arteries in ensuring blood flow continuity.

Table 1 presents the following parameters calculated for this 25-year-old volunteer: resistance index (RI) and pulsatility index (PI). The parameters at 20 ± 1°C were calculated using the equations for high-resistance vessels and the retrograde flow value RI_{V_d} (Eq. (5)), while the parameters at 30 ± 1°C were calculated using the equations for low-resistance vessels and the antegrade flow value $RI_{V_{ed}}$ (Eq. (6)). All parameters were computed by averaging values across three cardiac cycles.

As shown in Table 1, increasing the ambient temperature to 30°C resulted in a distinct reduction in peripheral resistance indices, which is associated with the development of systemic vasodilation. This effect reflects decreased vascular tone and increased volumetric blood flow.

Figure 6 presents diagrams of the resistance indices RI_{V_d} and $RI_{V_{ed}}$, calculated for a group of 15 study participants under different temperature conditions using Eqs. (5) and (6).

Table 1 Mean parameter values of the 25-year-old study participant under different ambient temperature conditions (based on data from Fig. 5).

Parameter	V_d (20 ± 1°C)	V_{ed} (30 ± 1°C)
RI (r.u.)	1.19	0.72
PI (r.u.)	3.64	1.25

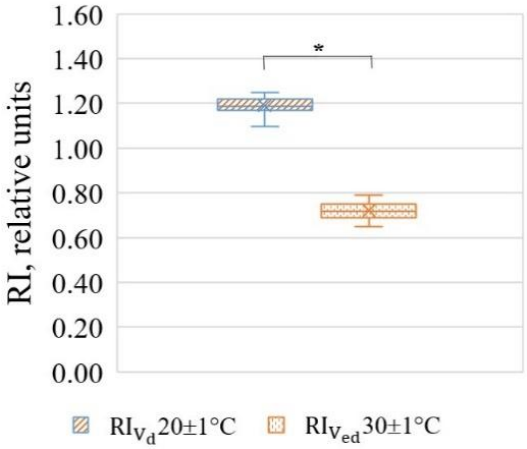


Fig. 6 Diagram of changes in resistance indices RI_{V_d} and $RI_{V_{ed}}$ in rooms with air temperatures of 20 ± 1°C and 30 ± 1°C. *Significance of difference in RI values between the two conditions: p = 0.0007.

The median resistance index decreased by 40%. Statistical analysis performed using the Wilcoxon T-test showed that the differences in resistance index values, calculated using both Eq. (5) and Eq. (6), at ambient temperatures of 20 ± 1 °C and elevated temperature of 30 ± 1 °C were statistically significant (p = 0.0007).

Figure 7 presents diagrams showing changes in the pulsatility indices PI_{V_d} and $PI_{V_{ed}}$ for the group of 15 study participants.

The median pulsatility index decreased by 64%. Statistical analysis using the Wilcoxon *T*-test demonstrated that the differences in pulsatility index (PI) values, calculated using both Eq. (7) and Eq. (9), between the ambient temperature of 20 ± 1 °C and the elevated temperature of 30 ± 1 °C were statistically significant (p = 0.0007).

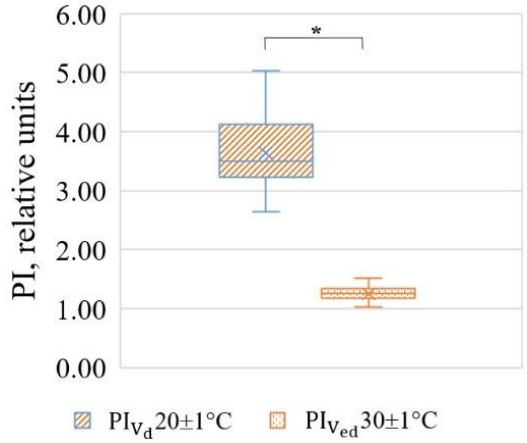


Fig. 7 Diagram of changes in the pulsatility indices PI_{V_d} and $PI_{V_{ed}}$ in rooms with air temperatures of 20 ± 1°C and 30 ± 1°C. *Significance of difference in PI values between the two conditions: p = 0.0007.

4 Discussion

The reduction in arteriolar vascular resistance is attributed to decreased sympathetic tone in the peripheral vascular system, the direct vasodilatory effect of heat on vascular smooth muscles, and the activation of local vasodilators. Under thermoneutral and cold conditions, the sympathetic division of the autonomic nervous system regulates cutaneous blood flow by modulating the frequency of tonic vasoconstrictor impulses [35]. This mechanism is suppressed during heating [22, 36, 27, 25].

Vasodilation can result from both reduced sympathetic activity and the influence of local metabolites (CO_2, H^+, K^+, adenosine, nitric oxide) and humoral factors reflecting current tissue demands for oxygen and nutrients. In some cases, local mechanisms ensuring adequate matching of blood flow to metabolic requirements may play a dominant role in regulating vascular tone [37, 38]. Specifically, activation of α1-adrenoceptors induces vasoconstriction, whereas stimulation of β2-adrenoceptors leads to vasodilation. Similar conclusions regarding the regulation of vascular tone in muscular-type arteries are reported by Tansey and Johnson [39].

Our analysis of blood flow using laser Doppler flowmetry enabled the determination of the mechanism behind changes in vascular resistance during body heating. The increase in the perfusion reflects enhanced volumetric blood flow in the microcirculatory bed, primarily associated with arteriolar dilation and, consequently, reduced tone in arterial vessels. The observed increase in the amplitude of neurogenic (An) and myogenic (Am) oscillations during whole-body thermal exposure is also linked to decreased tone in the microcirculatory bed, resulting from smooth muscle relaxation and microvascular vasodilation [40, 41].

Comparison of the results of ultrasound and LDF measurements demonstrates that Doppler ultrasound of the major vessels with the determination of indices RI and PI can serve as a tool for diagnosing the regulation of the general tone of peripheral microvessels. The ultrasound Doppler waveforms clearly reveals the outcome of the interaction between elastic and muscular arteries during heating. Elastic arteries (aorta, pulmonary arteries) are characterized by a predominance of elastic fibers in the tunica media, which enables their ability to stretch during systolic ejection and passively recoil during diastole. This mechanical property ensures continuous antegrade blood flow [42, 43].

Elastic arteries function as a damping mechanism: during systole, their elastic walls stretch due to incoming high-pressure blood, and during diastole, the walls return to their original state, promoting gradual blood movement to the peripheral sections of the vascular system. During body heating, increased cardiac output enhances volumetric blood flow in elastic vessels [24]. These functional characteristics of elastic arteries explain the observed changes in the Doppler spectrum: increased instantaneous and peak amplitudes of blood flow velocity values.

In contrast to elastic-type arteries, muscular-type arteries – including brachial, radial, and femoral vessels – possess a prominent layer of smooth muscle cells in the tunica media. This makes them more capable of active vasoconstriction and vasodilation in response to regulatory mechanisms [44]. Thermal exposure induces vasodilation in the microcirculatory bed, which influences blood flow characteristics in the arteries. This is manifested as reduced peripheral vascular resistance, evidenced by the disappearance of retrograde blood flow due to diminished contractile activity in muscular-type arteries. The decrease in peripheral resistance during heating reflects reduced arteriolar tone. Consequently, a reduction in RI and PI indices is observed during the thermal test.

It should be noted that in the case of certain vascular pathologies, for example, arterial stenosis, the ultrasound Dopplerogram will be strongly distorted, and it will be impossible to assess the tone of the arteries and microcirculatory bed in the corresponding area of the arterial vascular system. If the pathology is associated with atherosclerosis, which leads to increased stiffness of the vascular walls, then the shape of the ultrasound Dopplerogram and the corresponding coefficients will be a marker of changes in the tone of the smooth muscles of the vessels of the microcirculatory bed. Thus, the results obtained may be of practical importance not only in the case of a norm, but also in the case of a malfunction of the mechanisms of regulation of microvascular tone.

5 Conclusions

Laser Doppler flowmetry provides a comprehensive assessment of the vascular response, demonstrating an increase in the perfusion and the amplitudes of neurogenic (An) and myogenic (Am) oscillations during hyperthermia. This indicates the involvement of both sympathetic and local regulatory mechanisms in the process of adaptation to thermal stress.

Ultrasound Doppler proves to be an effective tool for evaluating peripheral resistance in major arteries. Our findings establish that the decrease in ultrasound Doppler ultrasound indices – specifically the resistance index (RI) and pulsatility index (PI), along with the increase in amplitudes of neurogenic (An) and myogenic (Am) oscillations during hyperthermia induced by the general thermal functional test, result from relaxation of smooth muscles and vasodilation of vessels in the microcirculatory bed.

Analysis of ultrasound Doppler data reveals that thermal exposure induces adaptive responses in different types of blood vessels. During whole-body heating, there is a reduction or complete disappearance of retrograde blood flow associated with altered tone in muscular-type vessels. Concurrently, the antegrade blood flow associated with elastic arteries maintains its positive direction.

Thus, the main result of this study is the demonstration that changes in ultrasound Doppler indices in the major arteries during heating can serve as an indicator of vascular resistance in the microcirculatory bed, in particular, in arterioles. Furthermore, ultrasound Doppler enables detection of changes in vascular resistance within a single cardiac cycle, while laser Doppler flowmetry requires substantially more time (minutes) to register comparable changes in vascular resistance compared to ultrasound Doppler.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data are available from the corresponding author on request.

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