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The effect of anesthetic induction on subcutaneous blood flow in various areas of the human face, assessed using infrared method based on three temperatures

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Assessment of microcirculation is of considerable interest in both research and clinical practice, as it provides information on local tissue perfusion. Information on the state of the microvascular bed is important in several metabolic and cardiovascular disorders, in critically ill patients, and during anesthesia. In this study, the feasibility of deriving clinically relevant parameters using infrared thermography was explored. The effect of anesthetic induction on the temperature dynamics of different facial regions driven by changes in blood flow was investigated. The method was based on a skin heat-balance model that enables estimation of thermal perfusion indices using three relevant temperatures (skin, ambient, core). The study was conducted in a cohort of patients undergoing anesthetic induction prior to cardiac surgery. The observed increases in thermal perfusion indices over the nose, cheeks, medial corners of the eyes, and forehead are most likely attributable to reduced sympathetic activity. The vasoplegic effect of anesthetic induction enabled validation of the proposed thermal method for assessing local perfusion abnormalities manifested on facial skin.

Keywords: infrared thermometry, anesthesia, propofol, perfusion, microcirculation.

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Introduction

Today, anesthesiology is an independent and crucial sector of medicine that focuses on studying various methods of pain relief and managing the human body during surgical operations and painful procedures [1]. Anesthetic support is a set of measures that ensure the patient's safety during anesthesia. The reduction or complete cessation of sensitivity is achieved through the partial or complete blocking of nerve impulses, resulting in removal or reduction of physiological responses to stimuli to an acceptable level. An essential component of anesthetic support is the management of consciousness and the elimination of the patient's presence during surgery. However, drugs that cause unconsciousness (hypnotics) often have a depressing effect on the cardiovascular system. In particular, the tone of blood vessels is normally regulated partly by the metabolic activity of nearby tissues, which leads to an increase in the vessels lumen in response to local signals of poor metabolism, and partly by the nerve pulses from the sympathetic nervous system (which provides a response to stress), which constricts the vessels. The heart sustains working pressure in this system by changing the force and frequency of heart contractions in response to the nerve signals on the walls stretching in large blood vessels (baroreflex). Hypnotics can disrupt this balance: blocking neural activity simultaneously leads to vasodilation and a decrease in the compensatory effect of the baroreflex. As a result, a condition develops when pressure drops, but the heart does not respond properly — this condition is called angioparesis. One of the most common hypnotics, propofol, also has this disadvantage.

Propofol (2,6-diisopropyl phenol) — is an intravenous drug that has been used for more than 30 years for sedation, induction (short-term, initial), and sustaining of general anesthesia [2,3]. Propofol is transported by blood proteins to its action site in the central nervous system, causing a sedative and hypnotic effect. The half-life of this drug is 2.5 minutes [4]. Despite its widespread use, the exact mechanism that causes loss of consciousness is still

unknown [5]. The drug is usually well tolerated by patients, and its dosage is easy to control, as 2,6-diisopropyl phenol is rapidly metabolized by the liver and excreted by the kidneys as inactive metabolic products [6]. All of this makes propofol a first-line hypnotic for sedation, anesthesia during surgical procedures, and, in particular, cardiac surgery.

The vasoplegic action of propofol [7] develops just as quickly — half-life of setting 5–10 min [6]. Propofol also reduces the overall level of sympathetic nervous activity and simultaneously weakens the baroreflex [8]. Therefore, in practice, its use requires constant monitoring of hemodynamic parameters. However, due to the lack of suitable clinical monitoring methods, the condition of microcirculation is often overlooked, despite its significant clinical importance. Thus, in study [9], it was shown using sublingual microscopy that the propofol-based anesthesia leads to a significant decrease in microcirculation parameters, such as functional density of microcirculatory vessels.

It is widely known that disturbances in microhemodynamics and tissue perfusion (blood supply) in critical conditions, as well as during anesthesia and in the perioperative period, lead to poorer outcomes for patients [10–12]. However, there are not enough methods for assessing microcirculation in clinical practice, and the methods that are used have many limitations. This urges the necessity of organizing an intraoperative microcirculation monitoring process based on a fast, non-invasive, and not requiring large computations thermal assessment method where the mid-infrared (IR) range of electromagnetic waves $8-14\,\mu$m would be applied. Thermal radiation data in this range could update the information obtained using other diagnostically useful non-invasive optical methods, such as diffuse reflection spectroscopy in the visible ($\sim 400-750$ nm) and near-infrared ($\sim 750-2000$ nm) ranges, which provides information about the amount of water in subcutaneous tissues [13].

Therefore, in this study, we used a previously developed method to assess the effect of general anesthesia on microcirculation. This method, based on infrared thermometry data, enables to estimate subcutaneous blood flow, which includes microcirculatory flow, using three relevant temperatures (room temperature, central temperature, and skin temperature) [12]. Using this method, we determined the amount of the blood flow-dependent heat exchange in several areas of interest on the face of 15 patients before and after anesthesia. We also tried to find correlations between the thermal indices of skin perfusion on the face (nose, forehead, cheeks, and medial corners of the eyes) and standard hemodynamic parameters (arterial, venous, and mean pressure, saturation O_2, and heart rate) during induction.

Experimental methods

A group of patients from Petrovsky National Research Centre of Surgery with various cardiovascular disorders and co-morbidities (see table) was examined. They were scheduled for cardiac surgery. The average age of patients was 63 ± 13 years. All participants of the study gave their voluntary consent to data processing.

On the day of operation, the Xenics Gobi-384 infrared camera with a microbolometer array detector with a sensitivity range of $8-14\,\mu$m was installed in the operating room 30 minutes before the operation for room-temperature thermolysis. On the evening before the intervention, patients received alprazolam 0.1 mg orally. Prior to 30–40 min before intervention promedol (trimeperidine) and suprastin (chloropyramine) were administered intramuscularly as premedication. Induction of anesthesia was performed using midazolam (0.02–0.03 mg/kg), propofol (1–2 mg/kg), and fentanyl ($2.5-3.5\,\mu$g/kg). Cisatracurium besylate was used for muscle relaxation at a dose of 0.15 mg/kg. At the preparatory stage, the patients were placed on a horizontal table (the table surface was heated to 37°C, and the operating room temperature was 20°C) in a supine position. After that, the IR camera was placed directly above the face so that the operator could obtain a clear thermal image and record a 10-second video fragment on a computer for further processing. On average, the recording was made 13 ± 5 min before induction of anesthesia (baseline), and 14 ± 9 min after induction of anesthesia.

The following areas of interest on the patients' faces were considered for thermographic imaging (Fig. 1, *a*): nose, cheeks at the center of the orbit and nose, medial angles of eyes, center of the forehead (sagittal plane), and periphery of the forehead (parasagittal plane passing through the areas on the cheeks). After the operation, thermal perfusion indices were calculated using the stationary three-temperature method described in [12]. In short, the model is based on the thermal balance equation of a skin area:

$$W_i - W_e = cm\frac{\Delta T_s}{\Delta t}, \tag{1}$$

where W_i — skin heating power from within deeper tissues, W_e — skin cooling power by surrounding environment, c — specific heat capacity of skin, m – mass of the studied skin area, T_s — its temperature. For simplicity, the model assumes that the powers are proportional to the temperature differences of the heat-exchanging reservoirs representing the skin, environment, and central part of the body:

$$W_i = h_i A(T_i - T_s), \tag{2}$$

$$W_e = h_e A(T_s - T_e), \tag{3}$$

where h_i, h_e — unknown heat-transfer coefficients, A — area of the studied skin region, T_i — inner temperature, T_e — outer temperature. The coefficient h_i in the model contains the main contribution as a convective heat transfer from the blood, as well as a side contribution — via thermal diffusion through the tissues. The he coefficient contains information about convective and radiative heat exchange with the room. Due to such notation equation (1) can be linearized, which allows for its analytical solution [12].

Patients info

Patient №	Gender	Age	Index of body weight	Pathology	Arterial hypertension (stage)	Smoking	Diabetes mellitus
1	m	69	25.25	coronary heart disease; atherosclerosis			
2	m	50	32.07	coronary heart disease; post-infarction cardio-sclerosis	3		
3	m	85	29.24	congenital heart disease; coronary heart disease; post-infarction cardio-sclerosis	3		+
4	m	63	33.24	coronary heart disease; post-infarction cardio-sclerosis	1		
5	m	64	26.22	aortic insufficiency; mitral insufficiency; tricuspid insufficiency	1		
6	m	62	16.79	mitral insufficiency		+	
7	m	76	24.91	aortic insufficiency; atherosclerosis		+	
8	m	66	33.08	atherosclerosis	1		
9	m	62	29.22	coronary heart disease; post-infarction cardio-sclerosis	1	+	+
10	m	74	33.41	coronary heart disease; atherocalcinosis	3		
11	f	68	26.53	coronary heart disease; atherosclerosis	3		+
12	f	69	29.3	congenital heart heart disease; atherocalcinosis	3		
13	m	38	29.3	hypertrophic cardiomyopathy; mitral insufficiency			
14	m	35	22.15	syndrome of connective tissue dysplasia			
15	m	69	22.77	mitral insufficiency	1		+

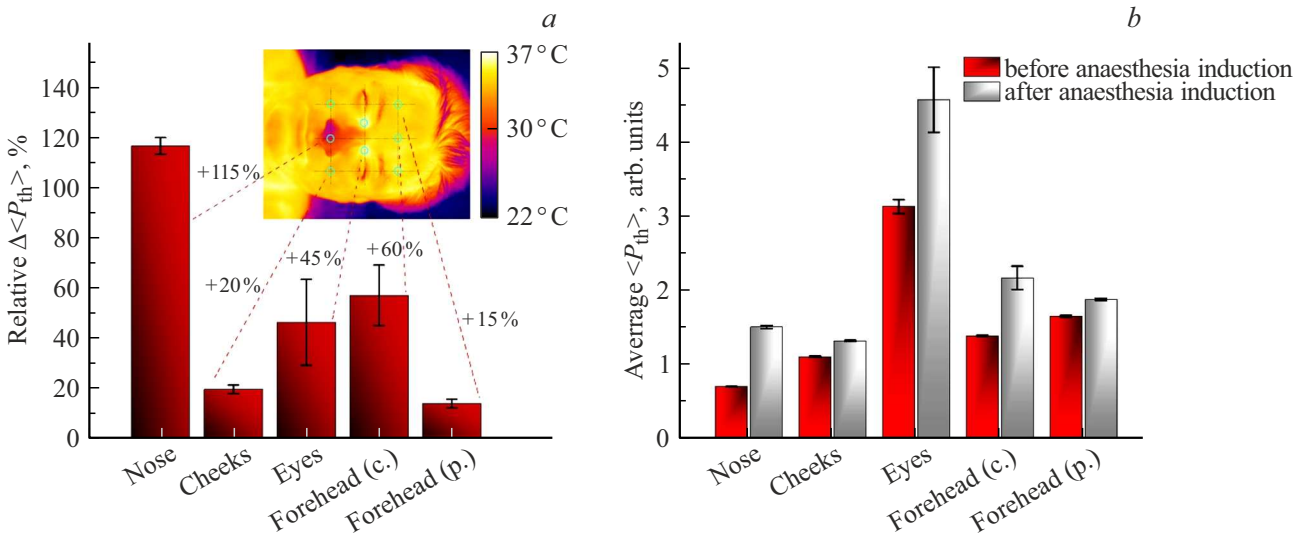

Figure 1. Thermal perfusion indices P_{th} found from equation (5) for the face areas of interest: (*a*) relative variation percentage compared to the initial level, (*b*) absolute group averages before and after induction of anesthesia. The inset in the Figure shows an example of a patient's thermal image before induction of anesthesia, with the areas of interest highlighted.

In this study, we assumed a steady (unchanging over the observation time scale Δt) blood flow, when $h_i \approx \text{const}$ and $\frac{\Delta T_s}{\Delta t} \to 0$. Then the equation (1) when substituting (2) and (3) into it is written in simple form

$$h_i(T_i - T_s = h_e(T_s - T_e). \qquad (4)$$

Under constant external conditions ($h_e \approx \text{const}$), the amount of blood flow at the moment of observation can be estimated based on the ratio h_i/h_e, which in this regard can be called the thermal index of perfusion P_{th} and which is directly expressed from (4):

$$\frac{h_i}{h_e} \equiv P_{th} = \frac{T_s - T_e}{T_i - T_s}. \qquad (5)$$

To assess T_s and T_e the IR camera was used, to assess T_i — esophageal thermometer data (GE *Healthcare, temperature probe series 400*). Blood pressure was measured using a catheter in the radial artery and recorded for later comparison. For all temperature measurements, the error was assumed to be 0.1°C.

To find the induction anesthesia effect, the results for the entire group of patients were averaged for the time points before and after the drug was administered. Statistical analysis of data was performed using SW *Microsoft® Excel® 2013* (15.0.4569.1504), *RStudio* (v. 2025.05.0 Build 496) and *STATISTICA* (v. 12). To ensure completeness of the analysis, a subsample of 6 patients was formed with the most complete and reliable volume of collected data, which included synchronous recordings of hemodynamic monitoring with thermographic examination in all areas of interest. Due to the limited sample size, the data distribution was assumed to be different from normal, and the non-parametric Spearman rank correlation coefficient was used to assess the correlation relationships r, which indicates a consistency in the monotonous nature of data changes.

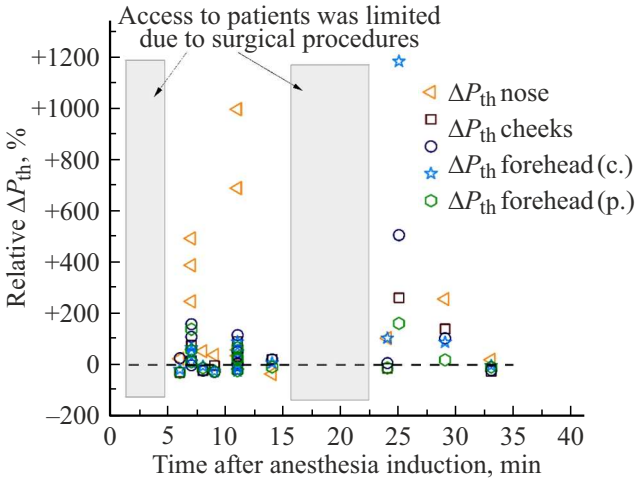

Figure 2. Individual changes in the thermal perfusion index depending on the time elapsed after administering propofol for each specific case. The time periods 0–5 min, 15–23 min, marked with gray rectangles, are associated with procedures performed by the surgical team that made it difficult to access the patient.

Results and discussion

The results of calculating the average thermal perfusion index $\langle P_{th} \rangle$ for all patients before and after induction of anesthesia are presented in Fig. 1 as relative and absolute values. On average, the blood flow in the examined areas of the patients' faces increased as a result of propofol effect within 15–115%.

It should be noted that some patients did not show any noticeable changes in blood flow, and some even showed a slight decrease, which can be visually assessed based on the data in Figure 2, where individual changes in thermal

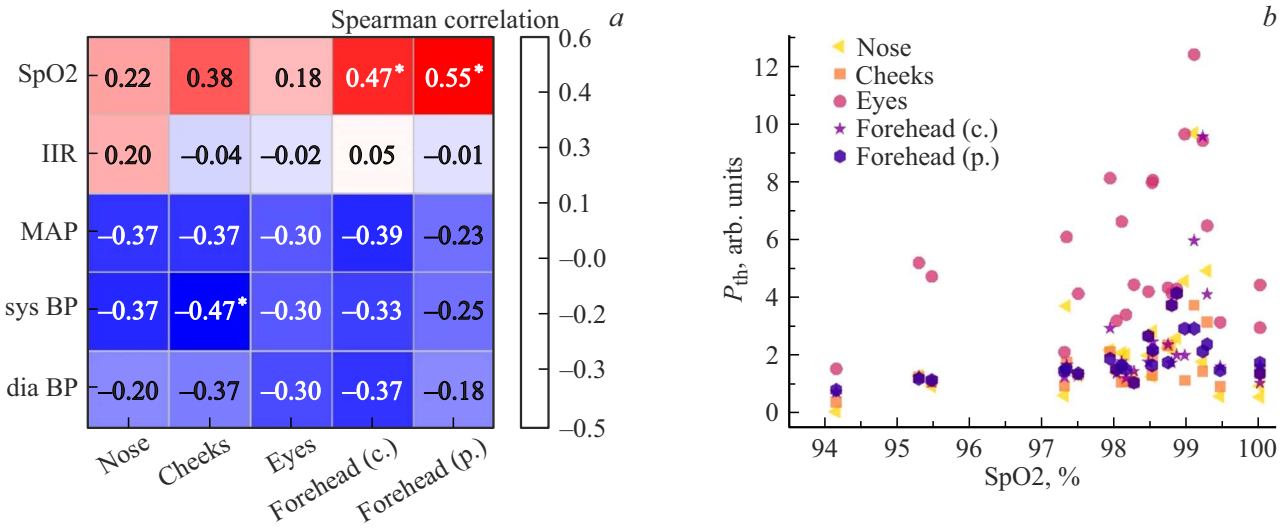

Figure 3. Hemodynamic data with thermal perfusion indices compared: (*a*) Spearman correlation thermal chat, where * means $p < 0.05$, (*b*) scattering diagram with individual dependencies P_{th} on SpO2 as an example for all patients in all face areas.

indices after induction anesthesia are plotted as a function of time elapsed after the end of induction anesthesia (the appropriate time point for recording was selected based on the specific operating conditions.). From the data presented in Fig. 2, it can be seen that in terms of frequency and amplitude the rise in the blood flow is mainly registered as a growing thermal perfusion index. It's worth noting that this effect is not caused by any heating that occurs after 5 minutes of anesthesia (for example, it is not related to warming up due to being unconscious on a heated table), since variation in observation times and body mass index does not affect the results. Most patients experience cold when they enter a well-ventilated operating room at 20°C, which is observed as an increased sympathetic regulation of the tone of the subcutaneous vessels in the nose, which is an area with a high concentration of vascular shunts that connect arteries and veins bypassing the capillary network — arteriovenous anastomoses [14]. When such shunts are closed, the subcutaneous blood flow drops rapidly, reducing heat loss to the environment and protecting the body from excessive heat loss. In thermal measurements, this manifests itself as a persistently low temperature in the nasal region before anesthesia (insert in Fig. 1, *a*), when the patient is still conscious, and this also explains the increased amplitude of blood flow growth in the nasal region after the onset of anesthesia.

To identify possible relationships with the hemodynamic pattern, a correlation analysis was performed: data on thermal perfusion indices P_{th} were compared with corresponding time-related data on the amount of oxygen bound to blood proteins (blood oxygen saturation, SpO2), heart rate (HR), pressure at the moment of maximum cardiac contraction (systolic blood pressure, sys BP), minimum contraction (diastolic blood pressure, dia BP), and mean arterial pressure (MAP). The analysis results are presented in Fig. 3,*a* as a color chart of the Spearman rank correlation coefficients. It can be seen that there are no significant correlations ($p < 0.05$)), and insignificant ones are negligible. This suggests that information about thermal indices does not reproduce central hemodynamics, but rather complements it.

The highest statistically significant correlation was registered between the blood saturation level SpO2 and thermal indices P_{th} in the periphery ($r = +0.55$, $p < 0.05$) and in the center ($r = +0.47$, $p < 0.05$) of forehead. Although these data need to be carefully rechecked on a larger group of patients, we consider them valuable because they can be explained by circulatory disorders associated with induction anesthesia. According to the pharmacodynamics of propofol [6], the drug causes a decrease in the level of sympathetic regulation of vascular tone, which reduces vascular resistance and leads to a higher blood pressure [15]. In particular, our small sample shows a moderate negative correlation of thermal index P_{th} of the cheeks with systolic blood pressure ($r = -0.47$, $p < 0.05$), and the entire set of pressures weakly negatively correlates with thermal indices of perfusion, forming a blue area on the thermal chart in Fig. 3, *a*. Low blood pressure with a weakened baroreflex is not compensated by the heart's work, resulting in the risk of tissue hypoxia. Physiological feedback mechanisms that locally increase blood flow by vasodilation (dilation of blood vessels) in response to increased concentrations of metabolites in venous blood [16] may no longer be able to adequately cope with the load due to reduced sympathetic regulation, resulting in a widespread vasodilation. Potentially, this condition of angioparesis can cause uneven blood supply to tissues [17]. In other words, if all collateral pathways for blood flow become open at the same time, there may not be enough oxygen at appropriate location at the right time, resulting in the phenomenon of oxygen

starvation. As a result, oxygen transport is compromised, which can lead to increased saturation against a backdrop of local tissue hypoxia. However, it cannot be ruled out that higher saturation in this case is related to the initiation of artificial lung ventilation.

Similar mechanisms are observed in sublingual studies of propofol effect on the microcirculation of the tongue mucosa. In the study [9], a transient decrease (-16%) in the number of perfused capillaries was found as a result of propofol effect which the authors also attribute to failure of the mechanisms of local vascular response to hypoxia. In [18], it was found that deterioration of capillary function during anesthesia and artificial circulation correlates with the level of lactate in the patients' blood, indicating a lack of oxygen in tissues. This may also be an evidence of the fact that microcirculation and tissue oxygenation are interrelated.

It should also be noted that the thermal indices of blood flow on the cheeks and nose have significantly different degrees of correlation with diastolic (~ 0.2) and systolic (~ 0.4) blood pressure. Diastolic pressure reflects the residual vascular resistance during diastole, while systolic pressure reflects the elastic properties of the walls and the force of cardiac contractions [19]. This suggests that difference analysis may be effective in evaluating specific parameters: in this case, the difference between the thermal indices of blood flow in the cheek region and forehead periphery may potentially display the force of cardiac contractions and the elastic response of the arteries. However, a more profound research is required to make an unambiguous conclusion.

Note that according to the data in [20], temperature variations are delayed relative to changes in blood flow. The value of this delay can be ~ 15 s for the phalanges of the fingers. In the context of this study, these observations mean that when calculating thermal blood flow indices based on time-series temperature data, a ± 15-second error should be taken into account.

Conclusions

In a group of patients with various cardiovascular pathologies, it was shown that thermal indices obtained from IR thermometry tend to rise during anesthesia induction, which can be explained by the increased peripheral blood supply to the skin associated with the procedure. In particular, it has been shown that growth can be observed in areas on the face. At the same time, different areas of the face seem to reflect different aspects of subcutaneous circulation that are not reflected in the hemodynamic data. Thus, blood circulation in the nasal area is more susceptible to stimuli that weaken sympathetic nervous regulation, while blood circulation on the forehead correlates better with peripheral oxygenation. Despite the fact that we did not observe any severe complications in our patient sample during induction of anesthesia, the experimental data obtained indicate the possibility of early detection of microcirculation disorders. This suggests that the method can be used to significantly improve intraoperative monitoring capabilities (including visualization, as shown in [21]), which can enhance patient safety during anesthesia.

Compliance with ethical standards

All procedures performed in the studies on humans complied with the ethical standards of the institutional and/or national research committee, as well as the 1964 Helsinki Declaration and its subsequent amendments, or comparable ethical standards. They were also approved by the local ethical committee of Federal State Budgetary Scientific Institution „B.V. Petrovsky National Research Centre of Surgery (Protocol № 1 of 24 January 2025).

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Conflict of interest

The authors declare that they have no conflict of interest.

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