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Ensuring optimal metabolism during coronary artery bypass grafting with cardiopulmonary bypass

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A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of the article

Aim: to reduce perioperative complications in cardiac surgeries with cardiopulmonary bypass (CPB) by developing a comprehensive, personalized approach to ensure optimal tissue metabolism.

Materials and methods. A comprehensive approach to metabolic monitoring and correction was tested on 25 patients who underwent minimally invasive coronary artery bypass grafting under CPB conditions. As a component of multimodal analgesia, Pectoralis Plane Nerve Block I (PEC I) and Pectoralis Plane Nerve Block II (PEC II) were performed. For energy monitoring, a computer program titled "Energy Monitoring During Cardiac Surgery" was developed. This program allows for the assessment of the degree of metabolic disturbances in real time and facilitates timely adjustments in therapeutic strategy. The study was divided into three stages: Stage 1 – pre-CPB, Stage 2 – during CPB, and Stage 3 – post-CPB.

Results. The functionality of the program was demonstrated using the case of a patient who underwent minimally invasive triple-vessel coronary artery bypass grafting. At Stage 1, the patient's baseline condition showed metabolic strain despite normal hemodynamic parameters. Performing PEC I and PEC II blocks improved the patient's metabolic status. During CPB, metabolism could be influenced by factors such as the composition and volume of the priming solution for the extracorporeal circuit, hemoglobin levels, perfusion index, gas-air mixture flow rate, patient body temperature, acid-base balance of the blood, and pharmacological regulation of vascular tone. Post-CPB, the indication for the use of sympathomimetics was a decrease in oxygen delivery and worsening metabolic parameters.

Conclusions. The use of the "Energy Monitoring During Cardiac Surgery" program enables real-time assessment of a patient's metabolic needs, allowing for informed decisions regarding therapeutic adjustments at all stages of the surgical intervention. Performing PEC I and PEC II blocks contributes to improved metabolism by reducing the severity of metabolic disturbances.

Keywords: ischemic heart disease, coronary artery bypass grafting, metabolism, energy monitoring, cardiopulmonary bypass, regional anesthesia.

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Забезпечення оптимального метаболізму при аортокоронарному шунтуванні зі штучним кровообігом

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Мета роботи – зменшення періопераційних ускладнень під час кардіохірургічних операцій із застосуванням штучного кровообігу (ШК) шляхом розроблення комплексного персоналізованого підходу для забезпечення оптимального тканинного метаболізму.

Матеріали і методи. Комплексний підхід до моніторингу та корекції метаболізму апробовано на 25 пацієнтах, яким виконано малоінвазивне аортокоронарне шунтування в умовах ШК. Як компонент мультимодальної аналгезії виконали блокаду Pectoralis Plane Nerve Block I (PEC I) та Pectoralis Plane Nerve Block II (PEC II). Для енергетичного моніторингу розроблено комп'ютерну програму «Енергомоніторинг під час кардіохірургічних операцій», що дає змогу оцінювати ступінь метаболічних порушень у пацієнта в режимі реального часу та своєчасно корегувати лікувальну тактику. Дослідження передбачало три етапи: перший – до ШК, другий – під час нього, третій – після ШК.

Результати. Роботу програми показано на прикладі пацієнта, якому виконано малоінвазивне аортокоронарне шунтування трьох судин. На першому етапі встановлено, що вихідний стан пацієнта супроводжувався метаболічним напруженням, але гемодинамічні показники залишалися нормальними. Блокади PEC I та PEC II покращили метаболічний статус пацієнта. Під час ШК на метаболізм можна впливати через склад і об'єм заповнення екстракорпорального контуру оксигенатора, рівень гемоглобіну, індекс перфузії, швидкість подачі газоповітряної суміші, температуру тіла пацієнта, кислотно-основного стану крові та шляхом медикаментозної регуляції судинного тонусу. Після завершення ШК призначення симпатоміметиків обґрунтоване зниженням доставки кисню та погіршенням метаболічних показників.

Висновки. Використання програми «Енергомоніторинг під час кардіохірургічних операцій» дає можливість у режимі реального часу оцінювати метаболічні потреби пацієнта та ухвалювати обґрунтовані рішення щодо корекції лікувальної тактики на всіх етапах оперативного втручання. Виконання блокад PEC I та PEC II сприяє покращенню метаболізму, зменшуючи вираженість метаболічних порушень.

Ключові слова: ішемічна хвороба серця, аортокоронарне шунтування, метаболізм, енергомоніторинг, штучний кровообіг, регіонарна анестезія.

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The primary objective of anesthesiologic-perfusion management during coronary artery bypass grafting (CABG) with cardiopulmonary bypass (CPB) is to maintain hemodynamic stability and balance oxygen delivery (DO_2) with oxygen consumption (VO_2) [1]. Any mismatch between DO_2 and VO_2 can contribute to postoperative complications [2]. In ischemic heart disease, ensuring adequate oxygen supply to tissues and mitigating the negative effects of oxygen debt are of paramount importance.

Surgical trauma is invariably accompanied by various changes in the adaptive-compensatory responses of the body, manifested as disruptions in homeostasis and metabolic parameters [3]. It is estimated that basal metabolic rate may increase by 10–25 % during surgical intervention; however, active energy production does not rise proportionately [4]. The increased energy expenditure in response to surgical trauma is associated with activation of the sympathoadrenal system: elevated catecholamine levels provoke oxygen consumption that exceeds its delivery capacity. Furthermore, catecholamines reduce the efficiency of energy production, leading to excessive oxygen and substrate consumption due to membrane and enzyme damage caused by free radicals, metabolic byproducts, and lipid peroxidation.

Aim

To reduce perioperative complications during cardiac surgeries with CPB by developing a comprehensive, personalized approach to ensure optimal tissue metabolism.

Materials and methods

The cardiac surgery team has several tools at its disposal to address the goals of this study.

Reducing the intensity of intraoperative trauma and surgical stress can be achieved through the choice of surgical access and the use of regional anesthesia techniques. One of the key advantages of minimally invasive CABG is reduced tissue trauma, achieved by employing thoracotomy instead of traditional sternotomy. This less invasive approach minimizes tissue damage, lowers the risk of infectious complications, and reduces intraoperative blood loss [5]. Patients undergoing minimally invasive surgery generally experience less severe postoperative pain, resulting in lower activation of the sympathoadrenal system and reduced stress hormone secretion. This, in turn, limits catabolic processes and decreases the body's energy expenditure, stabilizing metabolism. The reduction in metabolic stress ensures more efficient utilization of energy resources, accelerating postoperative recovery, while lower tissue trauma shortens rehabilitation periods and hospital stays [6].

Ineffective pain control increases the risk of cardiovascular and pulmonary complications and exacerbates stress responses, which may lead to hospital mortality [7]. To reduce intraoperative and postoperative pain, current research focuses on regional anesthesia under ultrasound guidance as part of multimodal anesthesia in cardiac surgery [8]. These methods include local anesthetic infiltration, neuraxial techniques such as thoracic epidural anesthesia (EA), and peripheral nerve blocks [9,10]. Peripheral nerve blocks are classified as low-risk interventions for bleeding and do not require specific time intervals before and after anticoagulant and antiplatelet administration, unlike EA [11].

In our center, during minimally invasive CABG, we perform Pectoralis Plane Nerve Block I (PEC I) as a component of multimodal analgesia, where a local anesthetic (25–50 mg of bupivacaine (longocaine) with an adjuvant – 4 mg dexamethasone) is injected between the pectoralis major and minor muscles at the level of the third rib *(Fig. 1)*. Additionally, we perform Pectoralis Plane Nerve Block II (PEC II), where the local anesthetic (50 mg of bupivacaine with 4 mg dexamethasone) is injected between the pectoralis minor and serratus anterior muscles at the level of the third rib *(Fig. 2)* [12].

The pectoral nerve block is a contemporary regional anesthesia technique first described by Blanco et al. in 2011. It involves the ultrasound-guided injection of a local anaesthetic into the tissue plane between the pectoralis major and pectoralis minor muscles to anesthetize the pectoral nerves. The use of interfascial blocks improves the quality of analgesia and significantly reduces the need for opioids and nonsteroidal anti-inflammatory drugs in the early postoperative period. This approach enhances anaesthetic management techniques for this patient population.

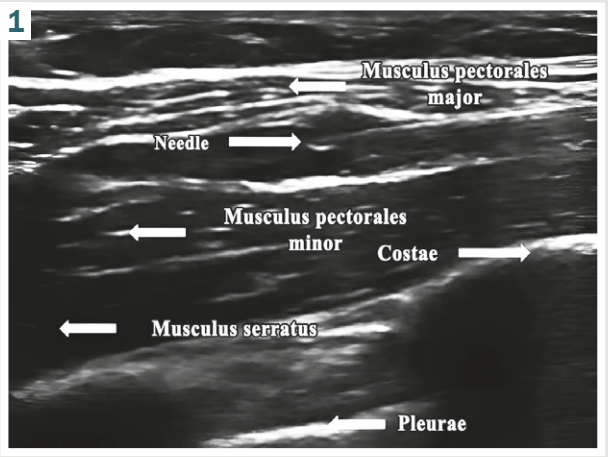
In our clinic, a protocol for anaesthetic management of cardiac surgery patients undergoing interfascial chest muscle blocks has been developed. This protocol is presented in *Table 1*.

Perioperative management during CABG is conducted in accordance with the developed protocol for managing patients with ischaemic heart disease [13].

Anaesthetic-perfusion management of metabolic regulation. At the State Institution of Science "Center of Innovative Healthcare Technologies" State Administrative Department, a computer program titled "Energy Monitoring During Cardiac Surgery". This program facilitates timely decision-making regarding adjustments in therapeutic strategies. It is a logical continuation of a previously developed method for perioperative energy monitoring of patients [14].

This program includes three stages of analysis. During the pre-(Stage I) and post-cardiopulmonary bypass periods (Stage III), the following parameters are recorded: patient age, sex, height, body weight, systolic blood pressure (SBP), diastolic blood pressure (DBP), heart rate (HR), haemoglobin levels (Hb), arterial (SaO_2) and venous oxygen saturation (SvO_2), venous blood pH, and HCO_3 at the time of assessment. During the cardiopulmonary bypass phase (Stage II), instead of SBP, DBP, and HR, mean perfusion pressure (MPP) and perfusion index (PI) are recorded. Additionally, the patient's body temperature is taken into account to adjust the metabolic rate calculations based on the CPB temperature conditions.

Based on these parameters, calculations are performed for the following: body surface area, mean arterial pressure, stroke volume, cardiac output, cardiac index, total vascular resistance index (TVRI), DO_2, oxygen delivery index, VO_2, oxygen consumption index, oxygen extraction ratio (O_2ER), oxygen extraction index (O_2EI),



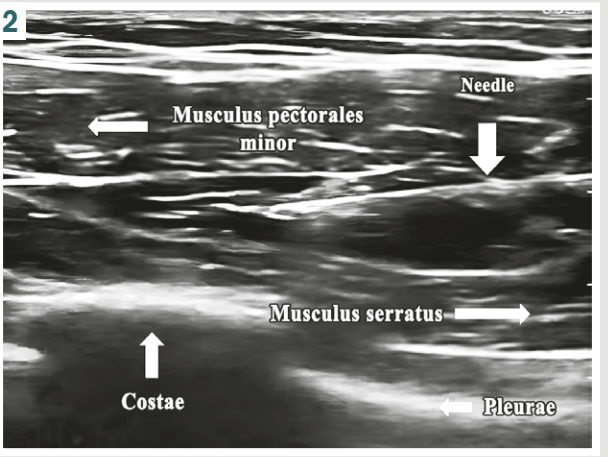


Fig. 1. Pectoralis Plane Nerve Blocks I.

Fig. 2. Pectoralis Plane Nerve Blocks II.

Table 1. Standard anaesthesia protocol with the use of interfascial blocks in cardiac surgery

Stage	Protocol
Monitoring	ECG in leads II, V5, oxygen saturation, invasive arterial pressure, central venous pressure, blood gases.
Premedication	Diazepam (2.5–5.0 mg), fentanyl (0.025–0.050 mg), paracetamol (Infuglan) 1000 mg IV.
Induction	Propofol 1.5–2.5 mg/kg body weight, titrated in increments of 30–40 mg. Muscle relaxation: atracurium besilate at a dose of 0.5–0.6 mg/kg body weight.
Maintenance	Oxygen-sevoflurane mixture with FiO_2 – 70 %, sevoflurane – 1.4–1.6 vol. % at a flow rate not exceeding 1 L/min. Muscle relaxation: fractional administration of atracurium besilate. Propofol 5–8 mg/kg/hour via infusion (during cardiopulmonary bypass).
Intraoperative analgesia	Fentanyl 0.03–0.05 mg/kg/min intravenously. Dexketoprofen (Dexalgin) 50 mg IV.
Regional anaesthesia methods under Ultrasound Guidance	Combination of blocks: SAP block / PEC I block / PEC II block, depending on the type of surgical intervention.
Postoperative analgesia	Dexketoprofen (Dexalgin) 1–2 mg/kg/day or paracetamol (Infuglan) 1–2 mg/kg/day IV. Morphine hydrochloride 0.125–0.500 mg/kg/day (if required).

metabolic rate (MR), metabolic rate index (MRI), target metabolic rate (TMR), target metabolic rate index, basal metabolic rate index, and metabolic disorder (MD).

MR refers to the patient's observed metabolic activity at a specific moment in time. TMR represents the desired optimal metabolic rate for the given patient, ensuring an oxygen balance without deficits at that specific moment. MD is calculated as the percentage deviation of metabolic rate from target metabolic [15].

The utilisation of this program enables real-time monitoring of metabolic dynamics at all stages of cardiac surgery, providing the opportunity for timely correction of metabolic disturbances.

Replenishment of energy substrates. One of the key responsibilities of an anaesthetist during cardiac surgery is to ensure the replenishment of expended energy, preventing the depletion of the body's energy reserves. Restoring energy substrates can help reduce the activation of the sympathoadrenal system, which in turn preserves autoregulatory mechanisms.

It is currently accepted that the primary energy source for the cardiac muscle is free fatty acids (FFAs), which are broken down into acetyl-Coenzyme A. This is subsequently oxidised in the tricarboxylic acid cycle and participates in oxidative phosphorylation. Glucose and lactate contribute a smaller portion of the heart's energy production. Myocardial FFA utilisation depends on the balance between carbohydrates and lipids involved in oxidative processes. Elevated concentrations of FFAs enhance their utilisation by the heart, whereas inhibition of lipolysis shifts the energy substrate preference toward glucose.

Myocardial blood flow is normally heterogeneous, leading to metabolic differences across various regions of the heart. Under aerobic conditions, blood flow and metabolism are closely interrelated. However, myocardial ischaemia disrupts metabolic processes in both ischaemic and intact zones. During ischaemia, glucose and lactate become the primary energy substrates, leading to impaired cellular homeostasis, the development of acidosis, and a reduction in ATP levels. In severe ischaemia, the myocardium loses its ability to utilise FFAs, and carbohydrates play a more significant role in meeting the heart's energy demands during functional stress.

Hypoxia highlights differences in the metabolism of energy substrates: glucose can undergo anaerobic metabolism, while FFAs require oxygen for their utilisation. Furthermore, lipid peroxidation is activated during ischaemia, causing cardiomyocyte damage. Following ischaemic episodes, the accumulation of circulating FFAs and their oxidation products reduces myocardial contractility and contributes to arrhythmias [16].

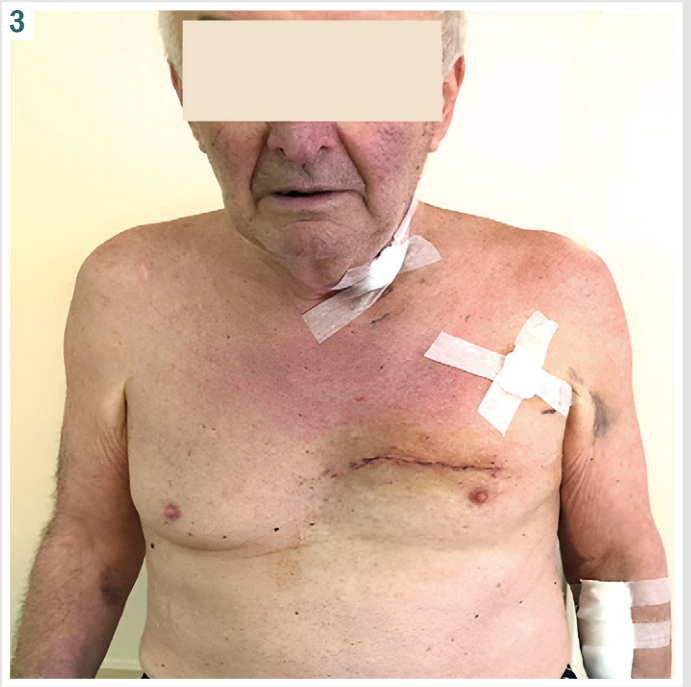


Fig. 3. Patient M., aged 75, who underwent minimally invasive CABG-3 under cardiopulmonary bypass conditions, with the use of PEC I and PEC II blocks and metabolic monitoring at three stages of the surgical intervention.

The use of glucose-insulin-potassium solution to maintain cellular energy potential, as well as the myocardial's electrolyte, biochemical, and functional integrity, enables effective metabolic protection of the myocardium [17,18].

The composition of the priming volume for the oxygenator's extracorporeal circuit during cardiac surgeries significantly impacts the patient's metabolism. Different types of solutions can cause varying degrees of haemodilution, which affects haemoglobin levels and, consequently, oxygen delivery to tissues.

The use of crystalloids alone may lead to a reduction in plasma oncotic pressure, promoting the development of oedema and impairing metabolic processes in tissues. Incorporating colloid solutions, such as albumin or synthetic colloids, helps maintain oncotic pressure and improves microcirculation, thereby positively influencing metabolism.

The priming composition also affects the electrolyte and acid-base balance, which are critical for cellular metabolic processes. Optimising the priming volume composition can support the energy status of cells and enhance overall metabolic stability [19].

Results

These approaches were tested on 25 patients at our clinic. Below, we present an illustration of the comprehensive approach to metabolic monitoring and correction using the case of Patient M., aged 75, weighing 78 kg, with a height of 171 cm, who underwent minimally invasive CABG-3 under cardiopulmonary bypass conditions *(Fig. 3)*.

The patient was admitted with the following diagnosis: Coronary heart disease. Effort angina, functional class III. Atherosclerotic and post-infarction cardiosclerosis (unknown duration). Stenosing atherosclerosis of the coronary arteries.

Coronary angiography performed on 04.06.2024. Left coronary artery ostium – 25 % stenosis. Left anterior descending artery: first segment – 50 % stenosis; second segment – 100 % occlusion. Circumflex artery: first segment – 50 % stenosis; second segment – 50 % stenosis; third segment – 75 % stenosis. Right coronary artery: first segment – 100 % occlusion. Hypertensive disease, stage III, grade 2, risk 4. Chronic heart failure stage IIA (left ventricular ejection fraction 55 %).

Date hospitalization: 10.06.2024. Date surgery: 11.06.2024. Date discharge from hospital: 18.06.2024.

In our clinic, as part of the Enhanced Recovery After Cardiac Surgery program, patients are admitted the day before surgery with results from a comprehensive preoperative evaluation package, which includes: fibrogastroduodenoscopy, complete blood count, urinalysis, blood biochemistry, syphilis serology, coagulation profile, blood type with Rh factor, chest X-ray, Doppler ultrasound of the neck and leg vessels, and echocardiography.

Additionally, all patients undergo mandatory evaluation by a neurologist and a computed tomography angiography of the major vessels with contrast enhancement. This is performed to promptly detect plaques, aneurysms, dissections, tortuosity, or foreign materials, ensuring safe vascular cannulation.

Premedication was administered on the operating table using diazepam (2.5 mg) and fentanyl (0.025 mg). Subsequently, radial artery catheterisation was performed for invasive arterial pressure monitoring.

According to the protocol, induction of anaesthesia was carried out with propofol at a dose of 1.5 mg/kg body weight, titrated in increments of 30–40 mg. Muscle relaxation was achieved with atracurium besilate at a dose of 0.5 mg/kg body weight.

A distinctive feature of minimally invasive cardiac surgeries is the requirement for femoral artery cannulation to establish CPB. In this process, oxygenated blood is delivered to the patient's body retrogradely. If effective cardiac activity and parallel perfusion are present, anterograde blood flow occurs in the aorta from the left ventricle. The gas composition of this portion of blood is independent of perfusion-related oxygenation and is entirely determined by gas exchange in the lungs.

Anterograde blood flow in the aorta during ineffective or disconnected mechanical ventilation can result in local hypoxaemia in the territories of the coronary arteries and branches of the aortic arch. Consequently, at certain stages of surgery, single-lung ventilation may be required.

In our practice, we use special double-lumen endotracheal tubes, available in left-sided or right-sided models with two inflatable cuffs (bronchial and tracheal). Inflation and deflation of these cuffs allow for the isolation of one lung. The longer part of the tube is inserted into the left or right main bronchus, while the shorter part is positioned in the distal trachea.

After intubation, catheterisation of the left internal jugular vein was performed via the "superior" approach

Table 2. Energy monitoring parameters of the patient at stage 1 before cardiopulmonary bypass

Parameter, units of measurement	Study period					
	1	2	3	4	5	6
Hb, g/L	130	129	125	125	122	120
SBP, mmHg	155	160	115	118	126	125
DBP, mmHg	75	90	65	69	72	85
HR, bpm	62	82	63	71	72	75
SaO_2, %	98	100	100	97	97	98
SvO_2, %	72	70	71	73	72	70
pH, units	7.336	7.354	7.371	7.324	7.326	7.401
HCO_3^-, mmol/L	25.6	24.6	25.6	27.4	26.8	25.7
TVRI, dyn×sec×cm^{-5}×m^{-2}	2971.32	4312.01	3789.26	3182.75	3394.51	6458.63
DO_2, mL/min	914.68	725. 13	602.04	695.21	671.29	591.08
VO_2, mL/min	242.66	217.53	156.53	172.01	173.01	168.88
O_2EI, %	26.53	30.00	26.00	24.74	25.77	28.57
MR, kcal/min	1213.31	1087.69	782.65	860.06	865.07	546.91
TMR, kcal/min	1157.80	1032.06	790.87	846.33	879.42	658.44
MD, %	-4.794	-5.390	1.040	-1.623	1.633	16.942

1: baseline parameters; **2:** tracheal intubation; **3:** PEC I and PEC II block; **4:** thoracotomy; **5:** harvesting of the mammary artery; **6:** cannulation of the femoral artery / vein.

using an 8 Fr, 15 cm double-lumen catheter. Monitoring of central venous pressure was initiated. Under sterile conditions, bladder catheterisation was carried out using a Foley catheter (14 Fr). An orogastric tube and a temperature probe were inserted into the oesophagus for temperature monitoring.

For analgesia before and after CPB, fentanyl was administered at a dosage of 0.03–0.05 mg/kg/min. Anaesthesia was maintained using a low-flow sevoflurane regimen at a concentration of 1.4–1.6 vol. %. Muscle relaxation was achieved with atracurium besilate at a dose of 0.3 mg/kg/hour administered intermittently. The infusion regimen consisted of 2.5–5.0 mL/kg of crystalloid solutions, with a preference for polyionic solutions. Prior to thoracotomy, PEC I and PEC II blocks were performed under ultrasound guidance. Heparinisation was conducted according to the standard protocol at 300 IU/kg body weight, monitored by activated clotting time.

Cardiopulmonary bypass was performed using a membrane oxygenator in a non-pulsatile flow mode under moderate hypothermia (32 °C). The priming volume of the extracorporeal circuit was 1300 mL, consisting of 700 mL of 4 % succinylated gelatin solution, 200 mL of 15 % mannitol, 200 mL of 4.2 % sodium bicarbonate solution, 200 mL of Reosorbilact, and 1.3 mL of heparin. Target blood flow rates were maintained at 2.3–2.5 L/min/m^2, with mean perfusion pressure kept within 60–80 mmHg. During perfusion, anaesthesia was maintained with propofol at a dosage of 5–8 mg/kg/hour via infusion. Analgesia was provided using fentanyl at 0.03–0.05 mg/kg/min, and muscle relaxation was achieved with atracurium besilate at a dose of 0.3–0.6 mg/kg/hour administered intermittently.

Throughout all three stages of the surgical intervention, metabolic dynamics were monitored, with the key parameters presented in *Tables 2, 3,* and *4*.

From the data in *Table 2*, it is evident that the patient's baseline condition was not accompanied by significant metabolic disturbances.

During tracheal intubation, the patient experienced an increase in arterial blood pressure, which, according to calculations, was associated with elevated systemic vascular resistance and heart rate (HR). Against this background, oxygen delivery to the tissues intensified, resulting in a slight shift in the metabolic balance toward hypermetabolism.

After performing PEC I and PEC II blocks, a decrease in oxygen consumption, a reduction in the O_2EI, and an improvement in the patient's metabolic status were observed.

In the course of thoracotomy stage, the patient was switched to single-lung ventilation of the right lung. Although the SaO_2 level was lower than in previous stages, metabolic disturbances were less pronounced due to a decrease in systemic vascular resistance (SVR) and normalisation of O_2EI. This trend persisted during the harvesting of the mammary artery.

During femoral artery and vein cannulation, a sharp increase in SVR occurred, leading to enhanced oxygen delivery to the tissues and more pronounced metabolic disturbances compared to earlier stages of the first phase of the study. This can be explained by a reflex response to manipulation of large vessels.

At the time of CPB, metabolism can be influenced by the composition and volume of the priming solution for the extracorporeal circuit, haemoglobin levels, perfusion index, gas-air mixture flow rate, patient body temperature, blood acid-base balance, and pharmacological regulation of vascular tone.

At the onset of perfusion, haemodilution has a significant impact on metabolism *(Table 3)*.

From the mathematical formula for calculating DO_2 to tissues, it follows that a decrease in haemoglobin leads to a reduction in DO_2. The compensatory mechanism involves maintaining the tissue perfusion index.

In our example, using the "Energy Monitoring During Cardiac Surgery" program, to sustain DO_2 at higher levels, the perfusion index had to be at least 2.2 L/min/m^2 with haemoglobin levels above 100 g/L and no less than 2.5 L/min/m^2 with haemoglobin levels below 90 g/L. CPB was conducted under moderate hypothermia, which facilitates reduced oxygen consumption.

Table 3 Energy monitoring parameters of the patient at stage 2 of the surgical intervention during cardiopulmonary bypass

Parameter, units of measurement	Study period			
	1	2	3	4
Hb, g/L	101	92	98	105
PI, L/min/m^2	2.3	2.5	2.5	2.3
Body temperature, °C	33.5	32.0	36.6	36.6
SaO_2, %	100	100	100	100
SvO_2, %	82	88	72	76
pH, units	7.362	7.413	7.351	7.33
HCO_3^-, mmol/L	22.45	26.1	22.5	24.1
TVRI, dyn×sec×cm^{-5}×m^{-2})	2955.48	2302.34	3038.95	2642.18
DO_2, mL/min	621.51	615.48	655.62	646.12
VO_2, mL/min	111.87	73.85	177.01	155.06
O_2ER, %	18.00	12.00	27.00	24.00
MR, kcal/min	559.35	338.52	885.09	775.34
TMR, kcal/min	551.29	367.18	540.39	857.18
MD, %	-1.461	5.568	14.921	9.544

1: start of cardiopulmonary bypass (5–10 minutes); **2:** 30–40 minutes of cardiopulmonary bypass; **3:** patient rewarming; **4:** before weaning from CPB.

Table 4. Energy monitoring parameters of the patient at stage 3 after cardiopulmonary bypass

Parameter, units of measurement	Study period					
	1	2	3	4	5	6
Hb, g/L	105	105	107	108	108	110
SBP, mmHg	90	122	125	115	118	26
DBP, mmHg	65	78	77	75	72	74
HR, bpm	69	86	89	86	85	85
SaO_2, %	97	99	100	100	100	100
SvO_2, %	68	72	75	77	77	75
pH, units	7.322	7.328	7.324	7.326	7.325	7.336
HCO_3^-, mmol/L	24.45	25.14	25.51	26.14	25.15	26.24
TVRI, dyn×sec×cm^{-5}×m^{-2}	4436.82	3980.85	3471.78	3862.44	3205.06	3125.12
DO_2, mL/min	359.87	517.99	613.21	528.27	629.45	687.59
VO_2, mL/min	107.59	141.27	153.30	121.50	144.77	171.89
O_2ER, %	29.89	27.27	25.00	23.00	23.00	25.00
MR, kcal/min	537.95	706.36	766.51	607.51	723.87	859.49
TMR, kcal/min	638.87	798.44	817.92	642.65	768.45	911.23
MD, %	15.797	11.537	6.281	5.468	5.802	5.679

1: CPB cessation, transition to autonomous cardiac activity; **2:** initiation of dobutamine infusion; **3:** administration of protamine; **4:** decannulation; **5:** suturing of the surgical wound; **6:** period prior to patient transfer to the intensive care unit.

Under hypothermic CPB, oxygen dissolved in the blood is actively extracted, while the extraction of haemoglobin-bound oxygen is limited. As a result, during the rewarming phase, metabolic manifestations of oxygen debt may occur. These are characterised by an increase in oxygen extraction by the tissues and a rise in metabolic disturbances.

The period before the end of perfusion is associated with the transition to two-lung ventilation and parallel perfusion, where the CPB machine operates simultaneously with the heart's own contractions. This requires adjustments in the patient's ventilation to prevent respiratory alkalosis.

After the cessation of CPB, a decrease in SBP and HR was observed, leading to a reduction in DO_2 and an increase in oxygen extraction by the tissues, which resulted in worsening metabolism *(Table 4)*.

The patient was prescribed dobutamine infusion at a rate of 3 mg/kg/min, which improved haemodynamics, reduced metabolic disturbances, and enhanced metabolism following CPB.

Discussion

Ensuring intraoperative safety for cardiac surgery patients requires comprehensive monitoring of haemodynamics and metabolism.

This approach enables personalised and integrated control of metabolic status, which serves as a key indicator of the interplay between energy balance, central haemodynamics, and oxygen status. These parameters reflect the adequacy and efficiency of perfusion in cardiac surgery patients under cardiopulmonary bypass conditions.

The primary goal of monitoring is to maintain an optimal balance between oxygen delivery and consumption, which may be disrupted due to surgical intervention or the patient's pre-existing critical condition.

The presented clinical case demonstrates the potential capabilities of energy monitoring in cardiac surgery procedures.

The analysis of *Table 2* data indicates that the absence of significant metabolic disorders prior to the initia-

tion of cardiopulmonary bypass was maintained due to an increased oxygen extraction index (O_2EI%), whose value slightly exceeded the norm. This suggests a strained state of cellular metabolic autoregulation at the baseline stage.

During tracheal intubation, considering the increase in SVR, the therapeutic strategy was aimed at reducing arterial blood pressure using vasodilators. It should be emphasised that relying solely on the parameters of SaO_2, arterial blood pressure, and HR displayed on the monitor, without taking into account metabolic parameters, would make it impossible to timely detect and adequately assess subclinical manifestations of metabolic disorders.

The result observed after performing PEC I and PEC II blocks can be explained by several mechanisms:

1. Reduction in pain levels: pectoral blocks provide effective regional analgesia, leading to a decrease in the patient's stress levels. This, in turn, reduces the activation of the sympathetic nervous system, lowering oxygen consumption by the tissues.

2. Reduction in metabolic load: the alleviation of pain and the suppression of stress responses contribute to a decrease in the overall metabolic load on the body, manifested as reduced oxygen consumption and a lower oxygen extraction index.

3. Improvement in tissue perfusion: blocking pain signals can improve regional microcirculation by reducing vasoconstriction. This enhances oxygen availability to the tissues and decreases the need for elevated oxygen extraction by cells.

4. Stabilisation of systemic haemodynamics: PEC I and PEC II blocks may also reduce the level of sympathetic nervous system hyperactivity, resulting in more stable haemodynamics. This decreases the burden on the cardiovascular system and, indirectly, improves the patient's metabolic status.

5. Overall improvement in oxygen balance: reduced tissue oxygen demand and a more uniform distribution of oxygen among organs and systems contribute to an improvement in the patient's metabolic status.

Thus, the combined effects of pectoral blocks on pain relief, haemodynamics, and metabolic processes ensure a reduction in oxygen consumption, a decrease in the oxygen extraction index, and an improvement in the patient's overall condition.

During the transition to one-lung ventilation of the right lung, a decrease in SaO_2 levels occurs due to the reduced surface area available for gas exchange. However, the metabolic disturbances in this case were less pronounced. This clinical situation can be explained by a reduction in systemic vascular resistance, which facilitates blood flow and improves oxygen delivery to tissues. The normalisation of the oxygen extraction index indicates more efficient oxygen utilisation by tissues. These changes suggest the body's adaptation and compensatory mechanisms that help maintain metabolic balance. A similar trend was observed during the mobilisation of the mammary artery, confirming a stable state of metabolic autoregulation.

A sharp increase in SVR during femoral vessel cannulation led to enhanced oxygen extraction by tissues, compensating for the reduced oxygen delivery caused by increased resistance. This may be associated with a reflex response to manipulations involving large vessels, including vasospasm and increased sympathetic activity, which impair systemic haemodynamics and increase the metabolic burden on tissues.

Metabolic monitoring plays a crucial role in the timely diagnosis and correction of changes occurring after cardiopulmonary bypass. At stage 3, the patient experienced a decrease in systemic arterial pressure and heart rate, leading to a reduction in oxygen delivery to tissues and a compensatory increase in oxygen extraction index. These changes indicated a deterioration in the patient's metabolic condition.

Thanks to the monitoring of metabolic parameters, it became possible not only to detect metabolic disturbances at an early stage but also to evaluate the effectiveness of therapy. Metabolic monitoring demonstrated that the infusion of dobutamine resulted not only in improved haemodynamics (increased DO_2) but also in a reduction of metabolic disturbances, confirming the efficacy of the therapy.

This approach to intraoperative patient management ensures a more personalised and targeted treatment strategy.

Conclusions

1. A comprehensive approach to metabolic control during minimally invasive CABG enables the adjustment of therapy at all stages of the surgical intervention.

2. Performing PEC I and PEC II blocks contributes to metabolic improvement by reducing the severity of metabolic disturbances.

3. Considering factors influencing metabolism during CPB, such as haemodilution, temperature changes, and the perfusion index, allows for the optimisation of extracorporeal circulation strategies to ensure adequate metabolic exchange.

4. The use of the "Energy Monitoring During Cardiac Surgery" program provides real-time assessment of the patient's metabolic needs and facilitates informed decisions on adjusting treatment strategies.

5. This approach enhances the efficiency of anaesthetic and perfusion management, allowing for the timely identification and adequate evaluation of subclinical manifestations of metabolic disturbances.

Prospects for further research. Future research will focus on studying the long-term benefits of using PEC I and PEC II blocks in minimally invasive heart surgeries. This will include evaluating their effects on postoperative pain management, metabolic stability, and the severity of postoperative pain syndromes.

Ethical approval
This study was conducted at the State Institution of Science "Centre of Innovative Healthcare Technologies" of the State Administrative Department, in accordance with the approval of the ethics committee (ethics committee protocol No. 4 dated 28.09.2023). Written informed consent to participate in the study was obtained from all patients.

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