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Severe Impairment of Microcirculatory Perfused Vessel Density Is Associated With Postoperative Lactate and Acute Organ Injury After Cardiac Surgery

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Abstract

Objective: Resuscitation after cardiac surgery needs to address multiple pathophysiological processes that are associated with significant morbidity and mortality. Functional microcirculatory

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Conflict of Interest

None. None of the authors has received any financial support or has a conflict of interest related to Cytocam or Braedius, BV.

derangements despite normal systemic hemodynamics have been previously described but must be tied to clinical outcomes. The authors hypothesized that microcirculatory dysfunction after cardiac surgery would include impaired capillary blood flow and impaired diffusive capacity and that subjects with the lowest quartile of perfused vessel density would have an increased postoperative lactate level and acute organ injury scores.

Design: Prospective, observational study.

Setting: A single, tertiary university cardiovascular surgical intensive care unit.

Participants: 25 adults undergoing elective cardiac surgery requiring cardiopulmonary bypass.

Intervention: Sublingual microcirculation was imaged using incident dark field microscopy before and 2 to 4 hours after surgery in the intensive care unit.

Measurements and Main Results: Compared with baseline measurements, postoperative vessel-by-vessel microvascular flow index ($2.9 [2.8-2.9]$ v $2.5 [2.4-2.7]$, $p < 0.0001$) and perfused vessel density were significantly impaired ($20.7 [19.3-22.9]$ v $16.3 [12.8-17.9]$, $p < 0.0001$). The lowest quartile of perfused vessel density ($<12.8 \text{ mm/mm}^2$) was associated with a significantly increased postoperative lactate level (6.0 ± 2.9 v 1.8 ± 1.2 , $p < 0.05$), peak lactate level (7.6 ± 2.8 v 2.8 ± 1.5 , $p = 0.03$), and sequential organ failure assessment (SOFA) score at 24 and 48 hours.

Conclusion: In patients undergoing cardiac surgery, there was a significant decrease in postoperative microcirculatory convective blood flow and diffusive capacity during early postoperative resuscitation. Severely impaired perfused vessel density, represented by the lowest quartile of distribution, is significantly related to hyperlactatemia and early organ injury.

Keywords

microcirculation; resuscitation; cardiac surgery; critical care; shock

RESUSCITATION AFTER cardiac surgery often needs to address and reverse multiple physiological derangements that can result in significant morbidity and mortality.^{1,2} After cardiopulmonary bypass (CPB), postoperative hypotension is associated with microcirculatory disturbances due to ischemic-reperfusion injury, systemic inflammatory response, and microemboli formation.³ Resuscitation often targets normalized systemic hemodynamic goals to achieve adequate tissue perfusion guided by lactate and oxygen-derived flow measurements. Optimized tissue perfusion represents the final pathway for cellular oxygenation and substrate delivery. Functional microcirculatory derangements have been described after cardiac surgery, but the relationship between microcirculatory impairment and perfusion-related parameters is unclear and must be tied to clinical outcomes.⁴⁻⁶

During the past decade, microcirculatory imaging technology has improved.⁷ Incident dark field (IDF) handheld videomicroscopy has improved compared with previous generations of microcirculatory imaging and produces higher quality images.⁷ As a result, more detailed, functional assessments of the human microcirculation can now be obtained.

Previous studies have found significant microcirculatory impairment after cardiac surgery with cardiopulmonary bypass.^{3,5,8} It is unclear, however, if the severity of early alterations

has an impact on meaningful clinical outcomes. Given the heterogeneity of hemodynamic disturbances that can arise after cardiac surgery, the authors hypothesized that severe alterations in microcirculatory function would be associated with the severity of postoperative lactic acidosis as well as increased postoperative organ dysfunction.

Methods

Study Design

This was a prospective study in a single, tertiary academic cardiovascular surgical intensive care unit (ICU). This study was approved by the authors' institutional review board (IRB # 829765), and written informed consent was obtained before enrollment. All consent forms were copied in triplicate, one given to the subject, the second placed in the official medical record, and the third kept in a secured location within the principal investigator's office. The goal was to observe the microcirculation before and after elective cardiothoracic surgery, during early resuscitation in the ICU.

Hemodynamic, laboratory, and microcirculation data were collected on each patient the day of surgery in the preoperative staging area (pre-CPB), followed by a second time point (post-CPB) during the early postoperative resuscitation period. Images were obtained within 2 to 4 hours after surgery in the ICU to identify early microcirculatory changes during the optimization phase of the clinical resuscitation, avoid interruption during patient handoff, and not interfere with initial clinical efforts. Systemic hemodynamic data along with perfusion data were collected at the time of IDF measurement. Study data were collected and managed using REDCap (Research Electronic Data Capture) electronic data capture tools hosted at the University of Pennsylvania.⁹

Inclusion and Exclusion Criteria

Adult patients (age >18 years) undergoing elective coronary artery bypass grafting or valvular surgery requiring cardiopulmonary bypass were eligible. Informed consent and study enrollment took place immediately before the procedure, in the preoperative staging area, or medical ward before their transfer to the operating room. Patients were excluded from the study if they received postoperative intravenous nitroglycerin, nicardipine, or systemic vasodilator infusions; had active cancer; or had taken metformin within 72 hours before surgery.

Microcirculatory Measurement and Analysis

Evaluation of the patient's sublingual microcirculation was recorded using incident dark field videomicroscopy (CytoCam, Braedius Medical BV, the Netherlands).¹⁰ At each time point, the video microscope was gently placed under the tongue until an adequate view of the microcirculation was acquired. A minimum of 3 video clips of 5 seconds' (100 frames) duration was included at each time point per analysis, with attention to quality factors, especially the absence of pressure artefact, excess saliva, and proper location in accordance with the accepted consensus for assessing the microcirculation (Figs. 1 and 2).^{11,12} Each clip was deidentified and coded to be analyzed after enrollment was completed. Microcirculatory videos were exported to automated vascular analysis (AVA 3.2, Microvision Medical B.V.)

format using the CCTools 2 software to be manually analyzed using a validated, web-based tool.¹³ Video analysis was performed at the conclusion of the data collection period by the lead investigator (J.C. G.), who was blinded to the conditions of the subject. Image quality was assessed using the 6-factor Massey quality score, which scores each video for appropriate illumination, duration, focus, content, stability, and pressure. Images were only analyzed if the Massey quality score was <10 .¹¹ Only microvessels $\geq 20\ \mu\text{m}$ in diameter were included in the analysis. Total vessel density, proportion of perfused vessels (PPV), perfused vessel density (PVD), vessel-by-vessel microcirculatory flow index (MFI_v), and microcirculatory heterogeneity index (MHI) were measured manually, according to the current best practice guidelines for reporting microcirculatory variables.¹² Blood flow within each microvessel was graded as having no flow, intermittent, sluggish, or continuous flow.¹² Vessels scored with intermittent or no flow were considered nonperfused, whereas continuous or sluggish scores were regarded as perfused vessels for the calculation of PPV and PVD.

Macrocirculatory and Physiological Measurements

Cardiac output, central venous pressure, pulmonary artery pressure, and mixed venous oxygen saturation (SvO₂) were measured continuously using a pulmonary artery catheter (Edwards Lifesciences LLC, Irvine, CA). Arterial blood pressure was measured using a standard invasive arterial line. Blood gas samples were drawn from an arterial line into a commercial, pre-heparinized 1-mL arterial blood sampler, then immediately analyzed with an ABL90 FLEX automatic blood gas analyzer (Radiometer America Inc., Brea, CA). Sequential organ failure assessment (SOFA) scores were calculated 24 and 48 hours after surgery.¹⁴

Perioperative Care

All patients were monitored with an invasive arterial blood pressure or noninvasive BP cuff, 5-lead electrocardiography, pulse oximetry, end-tidal capnography and gas analyzer, a pulmonary artery catheter with temperature probe, central venous pressure monitor, and transesophageal echocardiography. Induction of anesthesia was performed with intravenous fentanyl (up to $5\ \mu\text{g/kg}$), propofol (1 to $2\ \text{mg/kg}$), and vecuronium ($0.1\ \text{mg/kg}$) before endotracheal intubation. Anesthesia was maintained with isoflurane in a mixture of oxygen and air. Additional doses of muscle relaxants and fentanyl were given as needed. All patients were ventilated mechanically with lung-protective ventilation. Tidal volumes were titrated to 6 to $8\ \text{mL/kg}$ of ideal body weight and a positive end-expiratory pressure of 5 to $10\ \text{cm H}_2\text{O}$, with the respiratory rate adjusted to achieve an end-tidal carbon dioxide measurement of 30 to $35\ \text{mmHg}$. Before CPB, anticoagulation with $300\ \text{IU/kg}$ of heparin was administered to achieve an activated clotting time >450 seconds. A bypass flow rate of 2.2 to $2.4\ \text{L/min/m}^2$ with mean arterial pressure (MAP) maintained $>60\ \text{mmHg}$, administering intravenous phenylephrine as needed. After weaning from bypass, MAP was maintained $>60\ \text{mmHg}$ and cardiac index $>2.2\ \text{L/min/m}^2$ with the administration of fluid boluses, phenylephrine, and epinephrine infusion as needed. Postoperative cardiac function and filling status were optimized by transesophageal echocardiogram at the end of the procedure.

Heparin was reversed with protamine with a dose of 1 mg for each 100 IU of heparin to restore activated clotting time to baseline values.

ICU Resuscitation and Management

All patients were warmed to achieve normothermia and resuscitated to normalized systemic hemodynamic endpoints, including an optimized intravascular filling pressure, an MAP of 65 to 80 mmHg, and a cardiac index (CI) goal of >2.0 L/min/m². Mixed venous oxygen saturation was maintained between 60% and 70%, and lactate normalization was targeted. Phenylephrine was titrated to achieve a target MAP, and epinephrine was titrated to achieve an adequate CI after acceptable intravascular volume resuscitation. A repeated transthoracic echocardiogram was performed by the research team to evaluate left ventricular function during microcirculation assessment. A standard postoperative hemoglobin target of 8 g/dL was established for packed red blood cell transfusion.

Sample Size

This study was powered on the smallest difference between pre- and postoperative perfused vessel densities and between the highest and lowest quartile of postoperative SOFA scores using microcirculatory data from previous studies.^{15–17} The authors calculated that at least 18 patients would need to be enrolled to maintain 80% power to detect a significant difference in capillary flow, density, and SOFA scores. They increased this number to 25 patients to account for a variable magnitude of the effect.

Statistical Analysis

Statistical analysis was conducted using Prism v 8.0 (Graph-Pad Software, San Diego, CA). Data were assessed for normality using the D'Agostino and Pearson omnibus normality test. Global hemodynamic and microcirculation variables are reported as mean $\pm$ SD. Variables that were not normally distributed are reported as median with interquartile range (25th to 75th percentiles). Differences between variables at the initial (pre-CPB) and postoperative (post-CPB) time points were assessed using paired student *t* test or Wilcoxon matched-pairs signed rank test. Linear regression analysis was performed to determine whether PVD was an independent predictor of hyperlactatemia and postoperative SOFA scores. One-way ANOVA with Bonferroni post-hoc testing was performed to compare postoperative organ injury using 24- and 48-hour SOFA scores by PVD quartile.

Results

Study Population and Operative Details

The authors enrolled 25 subjects undergoing elective coronary artery bypass grafting surgery (CABG) or valvular surgery requiring cardiopulmonary bypass. Patient demographic and perioperative data are reported in Table 1. Common microvascular comorbidities included hypertension (84%), diabetes mellitus (32%), and chronic renal disease (20%). All subjects survived to hospital discharge.

Global Hemodynamics During Microcirculatory Measurement

Preoperative MAP was higher than postoperative MAP (94 ± 15 v 75 ± 9 mmHg; $p < 0.0001$). Pre- and postoperative cardiac index were similar (2.4 ± 0.7 v 2.5 ± 0.8 L/min/m²). Twenty-three patients required postoperative catecholamine support to achieve clinical macrocirculatory targets. Phenylephrine was used primarily to achieve target MAP, at a dose 0.82 ± 0.6 mcg/kg/min. Cardiac index, measured continuously by pulmonary artery catheter, was maintained with epinephrine, at a dose 0.05 ± 0.03 mcg/kg/min. Left ventricular function by point-of-care echocardiography was reassessed during microcirculation assessment and also unchanged. There was a statistically significant difference between pre- and postoperative central venous pressure, systemic vascular resistance, and lactate level despite postoperative macrocirculatory variables remaining within clinically acceptable range (Table 2).

Microcirculatory Measurements

A total of 280 microcirculation video clips were screened for quality. After image quality assessment, 175 video assessments met the quality threshold for further analysis. The analyzed image sequences had a mean Massey quality score of 0.5 ± 0.7 (illumination 0.06 ± 0.3 , duration 0.0 ± 0.1 , focus 0.1 ± 0.3 , content 0.0 ± 0.2 , stability 0.3 ± 0.4 , and pressure 0.1 ± 0.2).

Compared with baseline, postoperative microcirculatory convective flow was impaired, represented by a reduction in vessel-by-vessel MFI (pre-CPB v post-CPB MFIv: 2.9 [2.8 – 2.9] v 2.5 [2.4 – 2.7]; $p < 0.0001$) along with an increase in heterogeneity (pre-CPB v post-CPB MHI: 0.0 [0.0 – 0.2] v 0.5 [0.3 – 0.75]; $p < 0.0001$). Postoperative diffusive capacity was also impaired, as both proportion of perfused vessels (pre-CPB v post-CPB, PPV %: 94.3 [92.0 – 96.3] v 76.9 [68.5 – 85.0]; $p < 0.0001$) and perfused vessel density (pre-CPB v post-CPB, PVD: 20.7 [19.3 – 22.9] v 16.3 [12.8 – 17.9]; $p < 0.0001$) were reduced compared with preoperative baseline (Fig 3). Linear regression analysis did not find a correlation between postoperative MFIv and mean arterial pressure ($p = 0.75$) or cardiac index ($p = 0.35$). Postoperative perfused vessel density was not correlated with mean arterial pressure ($p = 0.63$) or cardiac index ($p = 0.67$). There was an inverse correlation between central venous pressure and microcirculatory flow index (MFIv $p = 0.01$, $r^2 = 0.25$) and PVD ($p = .02$, $r^2 = 0.23$). Catecholamine dose was not correlated with postoperative MFIv, MHI, total vessel density, or PVD ($p = 0.47$; $p = 0.95$; $p = 0.25$; $p = 0.86$).

To assess the clinical relevance of these results, several clinical, hemodynamic, and perfusion variables were compared by postoperative perfused vessel density quartile. Patients in the lowest quartile (<12.8 mm/mm²) exhibited higher postoperative lactate (Fig 4), peak lactate, and SOFA score at 24 hours compared with patients with a perfused vessel density in the upper 3 quartiles (Fig 5, Table 3).

Availability of Data and Materials

The data set supporting the conclusions of this article is available via the Zenodo research data repository.¹⁸

Discussion

Microcirculatory convective flow and diffusive capacity were impaired during early resuscitation in this cohort of patients after cardiac surgery. An acute reduction in small vessel capillary blood flow and increased heterogeneity were consistent with previous studies evaluating microcirculatory function after cardiac surgery requiring cardiopulmonary bypass.^{3,19} A number of potential causes have been suggested for the early loss of microcirculatory coherence with systemic hemodynamics, which include blood exposure to extracorporeal cardiopulmonary bypass circuitry, postoperative systemic inflammatory response syndrome (SIRS), ischemic-reperfusion injury, endothelial injury, impaired red blood cell rheology, or patient-specific hemodynamic endpoints that were outside generally accepted targets.^{5,20–23}

The most notable changes in patients' postoperative microcirculation were an increased heterogeneity, also referred to as a type 1 phenotype of microcirculatory dysfunction.¹² A type 1 loss represents microcirculatory dysfunction that is heterogeneous and can cause regional tissue hypoxia due to various cellular insults, including endothelial dysfunction, hemorheological changes, or abnormal vasomotor tone due to pathologic nitric oxide release or oxidative stress. In this cohort, a reduction in the proportion of perfused vessels appeared to contribute most to the reduction in perfused vessel density. Impaired PVD has been associated with poor clinical outcomes in patients with trauma and sepsis and has been identified at the initiation of cardiopulmonary bypass and other inflammatory conditions.^{24–26}

The authors also identified type 3 microcirculatory dysfunction, which was recognized by a reduction in postoperative vessel-by-vessel MFI and total vessel density. Type 3 dysfunction is seen as diffuse slowing of microcirculatory blood flow as a result of increased vascular resistance, and/or increased venous pressures. Postoperative central venous pressures decreased in the cohort, which made excessive postcapillary pressure a less likely cause of type 3 dysfunction. It is possible that a combined catecholamine therapy (phenylephrine and epinephrine) without concomitant vasodilator therapy could lead to excessive precapillary vasoconstriction. The authors did not include subjects who were prescribed concomitant vasodilators such as nitroglycerin, nicardipine, or phosphodiesterase inhibitors for inotropic support. Including these medications could improve postoperative microcirculatory function.^{6,27}

Within the study cohort, each patient's intravascular filling and cardiac function were assessed at the end of the operation by transesophageal echocardiogram to guide resuscitative interventions. Postoperative fluid resuscitation was guided by dynamic measures of volume responsiveness to avoid excessive crystalloid administration. Vasopressor and inotropic therapy were initiated if the patient needed additional hemodynamic support.^{28,29}

The effects of vasoactive medications on the functional microcirculation are incompletely understood but theoretically will directly affect capillary blood flow via precapillary sphincter augmentation. A majority of subjects in this study received phenylephrine to

reverse postoperative vasoplegia, and 4 patients received vasopressin in addition. Intraoperative phenylephrine, used to increase systemic vascular resistance after the initiation of cardiopulmonary bypass, has been found to reduce the sublingual small vessel MFI, with significant microcirculatory shunting toward vessels >25 micrometers in size.³⁰ This effect was not observed with postoperative phenylephrine use, with which a 20% to 30% increase in MAP did not change microvascular blood flow.³¹ Vasopressin appeared to affect microcirculatory blood flow less than other vasoactives when used to reverse SIRS-related vasoplegia.³²

Patients with chronic hypertension may require a more aggressive, individualized treatment strategy to ensure adequate end-organ perfusion after surgery.³³ The postoperative MAP targets were often lower than patients' preoperative measurements, to protect surgical anastomoses and avoid postoperative bleeding. Relatively low blood pressure targets in patients with chronic hypertension may contribute to microcirculatory impairment.

Epinephrine was used to augment cardiac index after adequate intravascular volume resuscitation. The macrocirculatory effects of epinephrine are well documented.^{34,35} Previous reports of epinephrine's effect on the splanchnic microcirculation have been mixed.^{8,36} In general, there is minimal evidence to suggest that epinephrine improves regional perfusion after cardiac surgery but can contribute to increased myocardial workload, oxygen consumption, and lactate production.^{37,38}

Other medications can also affect perioperative microcirculation, including continuous infusions of sedation and analgesics. All 25 subjects in this study received propofol as their primary sedative while intubated; however, emerging literature suggests that dexmedetomidine may decrease impairment of capillary convective blood flow and diffusive capacity.^{39,40}

Dexmedetomidine is a selective α_2 -adrenergic receptor agonist that affects endothelium-dependent vascular reactivity leading to an indirect vasodilatation through the reduction of central sympathetic activity, decreased peripheral release of norepinephrine, and increased local nitric oxide production.⁴¹

The relationship between microcirculatory impairment and perfusion-related clinical changes remains controversial. Lactic acidosis after cardiac surgery has been well-described, occurring in approximately 10% to 20% of patients and is associated with increased morbidity and mortality.⁴² The cause for postcardiopulmonary bypass lactic acidosis remains unclear, with a number of contributing etiologies that include tissue hypoxia, hyperglycemia, exposure to catecholamines, cardiopulmonary bypass, and mitochondrial dysfunction.^{43–45} Elevated lactate levels have been previously associated with changes in microcirculatory function, although this cohort appeared to have lactate levels that were much higher than those in previous studies.^{3,8,46} Lactate levels were inversely related to PVD, with the highest lactate levels found in patients with the most significantly impaired capillary blood flow (Fig 4). While this study did not allow for a causal relationship to be made, perfusion impairments can clearly result in hypoxic hyperlactatemia. Further investigation of the relationship between microcirculatory

alterations and lactate kinetics needs to be completed, to better understand the relationship between the microcirculation and postoperative lactate evolution.

Microcirculatory impairment has been associated with organ injury in patients with hemorrhagic, cardiogenic, and septic shock.^{47–49} The authors observed a progressive decline in PVD that was associated with an increased early SOFA score as well as postoperative lactate levels. Patients with the lowest PVD had both high lactate levels and increased SOFA scores. The authors hypothesized that the severity of early microcirculatory impairments reflects clinically relevant microvascular injury and impaired tissue oxygenation that lead to end-organ injury if left unaddressed. A resuscitation strategy that focuses primarily on catecholamines, without concomitant vasodilator therapy, may produce an unbalanced resuscitation toward excessive precapillary vasoconstriction leading to impaired tissue perfusion despite acceptable clinical end points.

Limitations

This study had several limitations. First, the observational nature of this study and smaller sample size hindered the ability to point to any direct effect of individual resuscitation efforts on clinical outcomes. This study was powered to find changes in microcirculatory function and extreme differences in SOFA score, which is a composite organ injury score. The authors acknowledge that the smaller sample size reduced the ability to differentiate between specific organ injuries within the SOFA score itself. Second, intraoperative microcirculation assessment would have helped better describe the dynamic changes that occurred after individual clinical interventions during the entire course of the patient's critical illness. This research study focused on the presence and relationship of early microcirculatory changes after surgery with clinical outcomes, but it did not assess for persistent microvascular dysfunction, which may also contribute to postoperative organ injury.^{47,50,51} Third, changes in convective flow were measured using vessel-by-vessel MFI, which is a more precise estimate compared with quadrant-based MFI measurement, but it is important to note that MFIv is only a semiquantitative measurement of capillary blood flow. Lastly, comparisons of microcirculation analysis between previous studies remain challenging as advancement in handheld videomicroscopy technology has improved significantly during the past 2 decades. Current generation IDF technology has allowed more detailed visualization of capillary density and function compared with previous orthogonal polarization spectral imaging and side stream dark field imaging.

Conclusion

In patients undergoing cardiac surgery, there was a significant postoperative decrease in both microcirculatory convective blood flow and diffusive capacity during early postoperative resuscitation. Severe derangements in capillary blood flow, specifically perfused vessel density, are associated with increases in postoperative lactate levels, peak lactate levels, and acute organ injury. Additional studies are required to investigate the relationship between alterations of the functional microcirculation and clinical outcomes after cardiac surgery.

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Fig. 1.

Experimental setup. (A) Patient positioning during IDF measurement. (B) Anatomic sublingual triangle where measurements were obtained.

Fig. 2. Representative still images of a patient's (A) baseline microcirculation and (B) impaired postoperative microcirculation.

Fig. 3.

Change in microcirculatory diffusive capacity after cardiac surgery with normal macrocirculatory measurements. A significant reduction in diffusive capacity (A) and convective blood flow (B). Scatter plot represents mean, with bars representing 95% confidence interval. * $p < 0.0001$.

Fig. 4.

Arterial lactate distribution according to PVD quartile. A significant difference between the lowest and highest PVD quartile was observed for (A) lactate at the time of microcirculation assessment and (B) patient peak lactate. * $p < 0.05$.

Fig. 5.

Postoperative day 1 SOFA score distribution according to PVD quartile. A significant difference between the lowest and all other PVD quartiles was observed. * $p < 0.05$. ** $p < 0.01$.

Table 1**Subject Characteristics and Demographics**

	n = 25	
Age, y	63	±12
Sex, male	20	80.0%
EuroSCORE II	2.0	
Performed operation		
CABG	10	40.0%
CABG + valve replacement/repair	6	20.0%
Valvular surgery only	9	40.0%
Comorbidities, n, %		
Hypertension	21	84.0%
Diabetes	8	32.0%
Heart failure with reduced ejection fraction (<30%)	2	8.0%
Chronic kidney disease	5	20.0%
Chronic obstructive pulmonary disease	1	4.0%
Perioperative details		
Cardiopulmonary bypass time, min	105	±35
Cross-clamp time, min	75	±27
Grafts, n	3	(2–3)
Cell saver transfusion, mL	752	±452
Red blood cell transfusion, n	15	60%
Fresh frozen plasma transfusion, n	5	20%
Platelet transfusion, n	8	32%
Crystalloid intravenous fluid, mL	1,231	±850
Urine output, mL	778	±478
CPB ultrafiltrate, mL	816	±1,288
SOFA score		
24 hours	6	(5–9)
48 hours	6	(2–8)
30-day survival	25	100%

NOTE. Data presented as mean ± standard deviation, median (quartile range), and frequency (%).

CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass;

SOFA, sequential organ failure assessment.

Table 2**Clinical Data**

	Before Bypass	After Bypass	p
Clinical and macrocirculatory data			
Temperature, °C	36.7 ± 0.3	36.6 ± 0.5	0.95
Heart rate, beats/min	73 ± 11	91 ± 9	<0.0001
Mean arterial pressure, mmHg	94 ± 15	75 ± 9	<0.0001
Central venous pressure, mmHg	13 ± 4	9 ± 3	0.0003
Cardiac index, L/min/m ²	2.4 ± 0.7	2.5 ± 0.8	0.56
Systemic vascular resistance, dyn/s/cm ⁻⁵	1,236 (1,128–1,617)	1,024 (955–1,214)	0.03
Left ventricular ejection fraction, %	50 (45–60)	60 (50–65)	0.006
Laboratory data			
Hemoglobin, g/dL	13.0 ± 2.1	12.4 ± 1.4	0.17
Hematocrit, %	37.1 ± 5.3	36.5 ± 4.3	0.18
PaO ₂ , mmHg	–	134 ± 60	–
Lactate, mmol/dL	0.8 ± 0.4	4.3 ± 2.7	<0.0001
Peak lactate, mmol/dL	–	5.3 ± 3.0	–
Mixed venous O ₂ saturation, %	–	69 ± 8	–
Vasopressor support			
Phenylephrine, n, mcg/kg/min	–	14; 0.6 (0.3–1.2)	–
Vasopressin, n, units/min	–	4; 0.03 (0.02–0.06)	–
Inotropic support, %, mcg/kg/min	–	–	–
Epinephrine, n, mcg/kg/min	–	20; 0.04 (0.02–0.06)	–

NOTE. Data are presented as mean ± standard deviation, median (quartile range), and frequency (%).

Table 3

Clinical Characteristics of Lowest Versus Upper Postoperative PVD Quartiles

Quartile	First	Second-Fourth	p
MAP, mmHg	76 (± 10)	74 (± 8)	0.62
Cardiac index, L/min/m ²	2.6 (± 1.1)	2.5 (± 0.6)	0.75
Central venous pressure, mmHg	11 (± 2.3)	8 (± 4)	0.15
Lactate, mmol/L	6.0 (± 2.9)	3.6 (± 2.4)	0.05*
Peak lactate, mmol/L	7.6 (± 2.8)	4.6 (± 2.7)	0.02*
SvO ₂ , %	73 (± 10)	68 (± 7)	0.15
SOFA 24 h	9 (8–11)	6 (5–7)	0.002*
SOFA 48 h	9 (6–11)	6 (2–7)	0.03*

NOTE. Data presented as mean $\pm$ standard deviation, median (quartile range), and frequency (%).

MAP, mean arterial pressure; PVD, perfused vessel density; SOFA, sequential organ failure assessment.