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Search for Fundamental Patterns in the Behavior of Integral Parameters of Cardiopulmonary Bypass for Rapid Assessment of Oxygen Balance During Cardiac Surgery

Abstract

Disruption of the balance between oxygen delivery and consumption remains a key contributor to metabolic disturbances and potential perioperative complications. This study explores the feasibility of calculating and applying the oxygen mass transfer coefficient (KO_2) as a core indicator of the mass-exchange capacity of the microcirculatory membrane. The proposed approach is grounded in the theoretical linkage between critical parameters of cardiopulmonary bypass (CPB) and the fundamental Fick's law, enabling a quantitative assessment of oxygen diffusion efficiency under artificial circulation conditions.

Objective. To improve the assessment of systemic oxygen balance during CPB by introducing an integral oxygen mass transfer coefficient (KO_2), which combines the main perfusion adequacy criteria based on Fick's principle.

Materials and Methods. A total of 129 intraoperative observations were analyzed during cardiac surgical procedures involving cardiopulmonary bypass (CPB). These data served as the basis for all necessary calculations to determine the oxygen mass transfer coefficient (KO_2). CPB monitoring parameters included standard acid–base balance and blood gas variables consistent with the alpha-stat strategy, based on Astrup's micromethod and the Siggaard–Andersen principles, using conventional blood gas analyzers. Additionally, physiological variables were taken into account, including hemodynamic indices, hematological status, anthropometric characteristics, as well as indicators of perfusion efficiency and metabolic balance.

Results. Within the framework of analytical validation, KO_2 dynamics demonstrated consistent behavior across both temperature groups and aligned with independent markers of tissue oxygenation status – specifically, increases in lactate levels and oxygen extraction, decreases in venous blood gas parameters, and shifts in acid–base balance. As these variables were not included in the clustering algorithm, their concordance supports the analytical independence and functional informativeness of KO_2. Furthermore, changes in KO_2 were often observed to precede alterations in metabolic parameters.

Conclusions. The construct validity of KO_2 demonstrated sensitivity to early alterations in oxygen balance and functional concordance with independent metabolic indicators, supporting its potential as a promising engineering parameter for automated assessment of oxygenation efficiency during cardiopulmonary bypass.

Keywords: *cardiopulmonary bypass, perfusion optimization, oxygen supply–demand balance, mass transfer coefficient, critical conditions, cardiac surgery.*

Introduction. Cardiopulmonary bypass (CPB) is an essential component of modern cardiac surgery, providing temporary support for systemic circulation and gas exchange during cardiac interventions. During surgery, the CPB system fully replaces the heart's pumping function and the lungs' oxygenation capacity, ensuring adequate oxygen delivery to vital organs under varying temperature conditions – an aspect that is critically important for preventing ischemic injury [1,2].

The assessment of perfusion effectiveness in clinical practice is based on a range of physiological parameters, including the perfusion index (PI), mean arterial pressure (MAP), mixed venous oxygen saturation (SvO_2), venous partial pressures of oxygen (PvO_2) and carbon

dioxide ($PvCO_2$), as well as acid–base balance variables. According to current international guidelines from the Extracorporeal Life Support Organization (ELSO) and the European Association for Cardio-Thoracic Surgery (EACTS), these parameters serve as key markers of systemic stability and adequate oxygenation [3,4].

Contemporary paradigms of perfusion management focus on maintaining the balance between oxygen delivery (DO_2) and oxygen consumption (VO_2), which is widely recognized as the primary determinant of «adequate» tissue perfusion. Targeted maintenance of this dynamic equilibrium is achieved through integrated control of hemodynamic variables and the blood's gas transport function, in accordance with established international clinical standards. As noted by Carrasco–Serrano and colleagues, maintaining this specific balance is critical for preventing acute ischemic complications and is associated with improved clinical outcomes in patients undergoing cardiopulmonary bypass [5].

Over the past decade, the integration of automated control systems into various aspects of cardiopulmonary bypass has progressed significantly. As early as the mid-1980s, Riley and colleagues described a microprocessor-based system for real-time data acquisition and processing, enabling continuous monitoring of key parameters and immediate alerting in the event of deviations [6]. Contemporary approaches now include automated temperature management (controlling the cooling and rewarming phases during CPB) [7], as well as continuous gas exchange monitoring using systems such as Quantum Perfusion [8], which enable automated regulation of blood parameters (PaO_2, $PaCO_2$, SvO_2) without the need for interval-based venous sampling.

However, traditional macrocirculatory criteria often fail to detect microcirculatory disturbances, particularly during prolonged hypothermia or reperfusion phases. As demonstrated by Kara et al., microcirculatory dysfunction may persist even when mean arterial pressure (MAP) and mixed venous oxygen saturation (SvO_2) remain within normal ranges, underscoring the need for additional monitoring parameters [9].

From a fundamental physiological perspective, oxygen transport across the microcirculatory membrane is governed by Fick's law, which states that the rate of mass transfer depends on the concentration gradient and the diffusional resistance of the membrane [10]. Nevertheless, under clinical CPB conditions, these processes are significantly complicated by phenomena such as shunting, alterations in capillary membrane thickness, and fluctuations in vascular resistance, necessitating the development of adaptive, clinically oriented models [11].

The dynamic variability of the living microcirculatory membrane necessitates the development of applied solutions to adapt classical mass transfer laws to the practical realities of cardiopulmonary bypass. Despite their chronological remoteness, a number of foundational studies remain scientifically relevant, as contemporary literature has yet to propose novel methodological frameworks for the quantitative assessment of these processes. A deeper understanding and clinical interpretation of regulated physiological parameters – grounded in the principles of fundamental physics – contribute to improving the diagnostic precision and therapeutic correction of oxygen balance disorders.

This study is intended for practicing perfusionists and proposes a practical framework for managing CPB based on the principles of oxygen mass transfer in a real circulatory system, logically derived from Fick's law.

The implementation of this study was made possible through the support of the M.M. Amosov National Institute of Cardiovascular Surgery of the National Academy of Medical Sciences of Ukraine. The research was conducted within the framework of an official cooperation agreement with the National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», which enabled the verification of the engineering concept in the context of real clinical cardiopulmonary bypass procedures. The authors express their sincere appreciation for the access to clinical materials and the facilitation of the research process.

Objective. To improve the assessment of systemic oxygen balance during CPB by introducing an integral oxygen mass transfer coefficient (KO_2), which combines the main perfusion adequacy criteria based on Fick's principle.

Working Hypothesis. According to Fick's law of molecular diffusion across a membrane surface, the amount of substance *dM* passing through an elementary surface area *dS* normal to the direction of diffusion over time *dt* is proportional to the concentration gradient *dC/dx* of the substance. The negative sign indicates that diffusion occurs in the direction of decreasing concentration:

$$\mathrm{dM} = -\mathrm{DdSdt}\frac{\mathrm{dC}}{\mathrm{dx}},$$

For real-world conditions of cardiopulmonary bypass, we proposed the assumption that the surface area *dS* of the microcirculatory membrane within the systemic capillary network is inversely proportional to the systemic vascular resistance index (SVRI). The oxygen concentration gradient *dC* between blood and mitochondrial tissue is maintained by the indexed arterial oxygen delivery (IDO_2), assuming that the mitochondrial oxygen concentration remains *Constant.* The flux *dM* across the microcirculatory membrane corresponds to the indexed oxygen consumption (IVO_2).

Given the dynamic changes within the microcirculatory network – including potential blood shunting – rather than using the classical diffusion coefficient *D,* (which is a *constant*), we introduced the oxygen mass transfer coefficient (KO_2), which reflects the dynamic properties of the microcirculatory interface.

As a result, we derived an equation that is conceptually linked to the fundamental law of membrane mass exchange but is based on measurable parameters relevant to artificial circulation:

$$\mathrm{dM} = -\mathrm{DdSdt}\frac{\mathrm{dC}}{\mathrm{dx}},$$

Here, IVO_2 serves as the functional equivalent of the flux *dM*; 1/SVRI represents the effective surface area *dS*; IDO_2 corresponds to the concentration gradient *dC*; and KO_2 is introduced as the functional equivalent of membrane permeability and thickness, analogous to *D/dx.*

Accordingly, Fick's law for oxygen transport across the capillary membrane can be reformulated as follows:

$$IVO2 = 10^{-5} \frac{KO2 \times IDO2}{SVRI}$$

To enable a quantitative assessment of oxygen transport efficiency under cardiopulmonary bypass conditions, the following equation for the oxygen mass transfer coefficient (KO_2) was proposed:

$$KO2 = 10^{-5} \frac{IVO2 \times SVRI}{IDO2}$$

Units of Measurement:

Oxygen Mass Transfer Coefficient – (KO_2) = $kg \cdot s^{-1} \cdot m^{-2}$

Indexed Oxygen Consumption – (IVO_2) = $mL/min/m^2$

Indexed Oxygen Delivery – (IDO_2) = $mL/min/m^2$

Systemic Vascular Resistance Index – (SVRI) = $dyn \cdot s \cdot cm^{-5} \cdot m^2$

The validity of the proposed equation is supported by the dimensional consistency of KO_2, expressed as $kg \cdot s^{-1} \cdot m^{-2}$. The oxygen mass transfer coefficient (KO_2) reflects the rate of oxygen transport through a unit surface area of the capillary membrane per unit time, serving as an integrated indicator of gas diffusion efficiency within the «cardiopulmonary bypass–organism system». The diffusional resistance of the membrane is defined as the reciprocal of KO_2 ($1/KO_2$), providing a measure of the barriers to oxygen transport.

Materials and Methods. The study included N = 129 intraoperative observations recorded between August 21, 2023, and May 2, 2025, during cardiac surgical procedures in n = 42 adult patients with acquired heart defects. The general characteristics of the patient cohort are presented in Table 1.

All surgical procedures were performed using conventional cardiopulmonary bypass (CPB) technology with central cannulation, ensuring effective anatomical decompression of the heart. The perfusion circuit consisted of a disposable Sorin Inspire 8 membrane oxygenation system with an integrated arterial filter, heat exchanger, and connection tubing. Perfusion flow was maintained using roller-pump heart–lung machines equipped with auxiliary temperature regulation systems. The mean duration of CPB was 230 ± 27 minutes.

Table 1

General characteristics of the patient cohort (n = 42)

Indicator, units	Value
Age, years	55.7 ± 12.6 (24; 76)
Height, cm	174.4 ± 8.9 (158; 190)
Weight, kg	93.7 ± 18.6 (50; 123)
Body surface area (BSA), m^2	2.08 ± 0.23 (1.50; 2.49)
Body mass index, kg/m^2	30.6 ± 4.9 (19.5; 38.7)
Female gender	14 (33.3 %)

To evaluate the impact of temperature strategy on perfusion efficiency, observations were stratified into two groups. The first group — normothermia (T ≥ 35 °C, N = 49) – corresponded to the controlled rewarming phase following the main surgical stage. The second group – moderate hypothermia (T = 28–32 °C, N = 80) – represented a targeted cooling strategy applied in accordance with myocardial and central nervous system hypothermic protection protocols.

Comprehensive assessment of perfusion status included measurements of hemoglobin concentration (Hb) and hematocrit (Hct) as blood rheological parameters, along with systemic hemodynamic indicators: mean arterial pressure (MAP), central venous pressure (CVP), and perfusion index (PI), normalized to body surface area (BSA) calculated using the Du Bois formula.

Blood gas monitoring encompassed mixed venous oxygen saturation (SvO_2), partial pressures of venous oxygen (PvO_2) and carbon dioxide ($PvCO_2$), oxygen content in arterial (CaO_2) and venous (CvO_2) blood, as well as pH, base excess (BE), lactate, and oxygen extraction ratio (O_2ER).

For each observation, indexed oxygen delivery (IDO_2), indexed oxygen consumption (IVO_2), and systemic vascular resistance index (SVRI) were calculated. Based on these variables, the oxygen mass transfer coefficient (KO_2) was derived to reflect oxygenation efficiency under the perfusion gradient, using the following original formula:

$$KO2 = 10^{-5} \frac{IVO2 \times SVRI}{IDO2}$$

Perfusion status stratification was performed using k-means clustering (k = 3), applied separately within each temperature group. The clustering model included only three variables – IVO_2, IDO_2, and SVRI – which constitute the analytical basis of the KO_2 formula. Prior to clustering, all input data were standardized using z-score normalization to ensure equal weighting of variables within the multidimensional space.

Each observation was automatically assigned to one of three clusters, which were subsequently ordered by the median IVO_2 value and conditionally designated as states of reduced (Cluster 1), physiologically appropriate (Cluster 2), or elevated (Cluster 3) oxygen consumption.

Despite a limited number of observations in some clusters (N = 10–26), the clustering approach is methodologically justified due to the low dimensionality of the model, the homogeneity of the stratified cohort, the a priori definition of cluster number, and the non-inclusion of KO_2 in the clustering algorithm – used exclusively for analytical validation.

Additional credibility was ensured through post-clustering statistical validation: for each cluster, descriptive analysis was performed on key parameters (IVO_2, IDO_2, SVRI, KO_2), along with supplementary indicators of

macrocirculation and metabolism (MAP, PI, SvO_2, PvO_2, CaO_2, CvO_2, $PvCO_2$, O_2ER, pH, BE, lactate). Intercluster differences were tested for statistical significance using Welch's t-test, with a significance level of $\alpha = 0.05$.

Results. Analysis of the stratified normothermic (Table 2) and moderately hypothermic (Table 4) groups revealed consistent patterns between oxygen consumption levels and the behavior of the oxygen mass transfer coefficient (KO_2). Within each temperature group, k-means clustering distinguished three functional states – reduced, physiologically appropriate, and elevated VO_2 – accompanied by coherent shifts in lactate levels, diffusion-related transport indices, and metabolic responses. Below are the results for each temperature strategy considered separately.

In the normothermic group (N = 49), the sequential ordering of clusters reflected a progressive increase in VO_2 and was associated with corresponding rises in venous lactate concentration (from 1.63 ± 0.59 to 3.52 ± 1.74 mmol/L), indexed oxygen consumption IVO_2 (from 87.46 ± 20.65 to 133.19 ± 19.78 mL/min/m^2), and oxygen extraction ratio O_2ER (from 20.11 ± 3.76 % to 28.00 ± 4.50 %). These changes were accompanied by progressive acidosis, with pH decreasing from 7.39 ± 0.04 to 7.31 ± 0.05, a rise in base deficit (BE from 0.52 ± 2.45 to –4.01 ± 3.35 mmol/L), and a compensatory reduction in $PvCO_2$ (from 40.11 ± 5.27 to 38.43 ± 5.22 mmHg).

According to the working hypothesis, the conditional equivalent of microcirculatory membrane surface area – SVRI – remained statistically unchanged between Clusters 1 and 3 (p = 0.5744), as reflected by their respective mean values: 2331.35 ± 383.34 and 2398.69 ± 338.54 dyn·s·cm^{-5}·m^2. In contrast, transmembrane oxygen transport (KO_2) was significantly higher (p = 0.0029) in Cluster 3, with elevated consumption (0.0071 ± 0.0012 kg·s^{-1}·m^{-2}) compared to Cluster 1 (0.0059 ± 0.0010 kg·s^{-1}·m^{-2}). This difference may be explained by a pronounced metabolic demand and the presence of oxygen debt. The latter is confirmed by the highest lactate concentration – 3.52 ± 1.74 mmol/L – recorded in the third normothermic cluster.

The differences between Clusters 1 and 3 reflect a progressive increase in metabolic oxygen demand during the rewarming phase, which logically enhances oxygen transport intensity and results in a corresponding elevation of the mass transfer coefficient.

Cluster 2, characterized by a conditionally physiological level of VO_2, proved to be the most informative for evaluating the physiological relevance of the oxygen mass transfer coefficient (KO_2). Despite reduced oxygen delivery (IDO_2 = 283.14 mL/min/m^2), this cluster exhibited the highest systemic vascular resistance (SVRI = 3604 dyn·s·cm^{-5}·m^2), which resulted in a localized and dataset-wide maximum KO_2 value of 0.0082 kg·s^{-1}·m^{-2}.

This parameter configuration reflects pronounced functional stress within the microcirculatory system, manifesting as an increased diffusive workload required to maintain adequate oxygen consumption (VO_2). These changes most likely reflect the activation of compensatory mechanisms within the microcirculation, particularly the redistribution of blood flow between regions with high and low metabolic demands («hungry» and «satiated» zones). This observation is consistent with the adapted model of dynamic capillary flow heterogeneity implemented via cellular automaton modeling, as presented in the study by Ye Nastenko [12].

The increase in transmembrane oxygen transport was further supported by the presence of an oxygen debt, as evidenced by elevated lactate levels in Cluster 2, though less pronounced than in Cluster 3. Thus, the cumulative effect of oxygen debt and compensatory membrane dynamics under reduced oxygen delivery led to the highest KO_2 value observed in the normothermic group.

Hemodynamic parameters such as mean arterial pressure (MAP) and perfusion index (PI) remained stable across all clusters, indicating macroscopic compensatory integrity of the system. In contrast, gas exchange variables defining the oxygen gradient showed characteristic trends: partial pressure of venous oxygen (PvO_2), mixed venous oxygen saturation (SvO_2), and venous oxygen content (CvO_2) progressively decreased alongside an increasing oxygen extraction ratio (O_2ER). This pattern reflects a growing concentration gradient and, in accordance with Fick's law, enhanced transmembrane oxygen mass transfer.

Simultaneous increases in lactate concentration and decreases in pH and base excess (BE) suggest an elevated metabolic load that could not be fully compensated by oxygen delivery alone, necessitating additional activation of extraction mechanisms. Thus, KO_2 served in this subgroup as an integrated engineering indicator, capturing both the oxygen delivery gradient and microcirculatory membrane resistance, demonstrating sensitivity to changes in VO_2 and tissue metabolic stress.

For most variables analyzed, statistically significant inter-cluster differences were observed (Table 3). Exceptions included indexed oxygen consumption (IVO_2) between Clusters 1 and 2, and systemic vascular resistance index (SVRI) between Clusters 1 and 3, where no statistically significant differences were detected (p > 0.05).

Thus, during the normothermic perfusion phase (rewarming), the oxygen mass transfer coefficient (KO_2) demonstrated high sensitivity to changes in perfusion status, enabling clear differentiation between clusters and showing a strong association with vascular resistance mechanisms, oxygen transport gradient, and tissue metabolic response.

In the moderate hypothermia group (N = 80; T = 28–32 °C), KO_2 preserved a similar trend – its values corresponded to a stepwise increase in oxygen consumption (from 48.36 ± 10.08 to 111.83 ± 18.29 mL/min/m^2), demonstrating a positive correlation with oxygen debt indicators (lactate increase from 2.08 ± 0.79 to 4.27 ± 1.66 mmol/L), indexed oxygen consumption (IVO_2), and oxygen delivery (IDO_2: from 272.18 ± 48.73

Table 2

Clustering of oxygen transport, gas exchange, and metabolic parameters under normothermia (T ⩾ 35 °C), based on IVO_2, IDO_2, and SVRI

Parameter (unit)	↓VO_2 (Cluster 1)	↔VO_2 (Cluster 2)	↑VO_2 (Cluster 3)
Number of observations (N)	25	10	14
IVO_2 (mL/min/m²)	87.46 ± 20.65	90.39 ± 18.76	133.19± 19.78
IDO_2 (mL/min/m²)	350.50 ± 40.87	283.14 ± 56.17	409.38 ± 39.87
SVRI (dyn·s·cm^{-5}·m²)	2331.35 ± 383.34	3604.23 ± 697.48	2398.69 ± 338.54
KO_2 (kg·s^{-1}·m^{-2})	0.0059 ± 0.0010	0.0082 ± 0.0013	0.0071 ± 0.0012
MAP (mmHg)	77.64 ± 11.88	77.90 ± 10.51	75.64 ± 11.39
SvO_2 (%)	79.50 ± 6.45	75.00 ± 6.79	73.36 ± 6.58
PvO_2 (mmHg)	44.83 ± 6.91	39.83 ± 5.64	38.14 ± 6.53
CaO_2 (mL/dL)	14.71 ± 2.28	13.24 ± 2.01	15.74 ± 1.94
CvO_2 (mL/dL)	11.75 ± 1.92	9.87 ± 1.85	11.31 ± 1.86
PI (L/min/m²)	2.66 ± 0.44	2.34 ± 0.37	2.74 ± 0.46
$PvCO_2$ (mmHg)	40.11 ± 5.27	39.11 ± 4.84	38.43 ± 5.22
O_2ER (%)	20.11 ± 3.76	25.20 ± 3.67	28.00 ± 4.50
Lactate (mmol/L)	1.63 ± 0.59	2.38 ± 0.81	3.52 ± 1.74
pH	7.39 ± 0.04	7.35 ± 0.05	7.31 ± 0.05
BE (mmol/L)	0.52 ± 2.45	-2.05 ± 2.88	-4.01 ± 3.35

Table 3

Statistical validation of inter-cluster differences under normothermia using Welch's t-test

Parameter	t (1 vs 2)	p (1 vs 2)	t (1 vs 3)	p (1 vs 3)	t (2 vs 3)	p (2 vs 3)
IVO_2	-0.40	0.6903	-6.82	<0.0001	-5.39	<0.0001
IDO_2	3.44	0.0044	-4.38	0.0002	-6.09	<0.0001
SVRI	-5.45	0.0002	-0.57	0.5744	5.06	0.0003
KO_2	-7.27	<0.0001	-3.32	0.0029	4.09	0.0007

to 397.90 ± 57.18 mL/min/m²), while systemic vascular resistance remained stable (SVRI: from 2735.10 ± 446.24 to 2486.17 ± 464.39 dyn·s·cm^{-5}·m²).

The association between KO_2 and metabolic demand, as predicted by the working hypothesis, is supported by its elevated values in clusters with higher lactate (up to 4.27 ± 1.66 mmol/L), accompanied by progressive changes in pH (from 7.35 ± 0.04 to 7.30 ± 0.04) and base excess (from -1.32 ± 3.02 to -5.10 ± 2.44 mmol/L), confirming the model's sensitivity to metabolic shifts.

Gas exchange parameters further validated the stratification logic: with increasing VO_2, there was a consistent decrease in PvO_2 (down to 33.75 ± 5.47 mmHg), SvO_2 (down to 67.75 ± 7.05 %), and CvO_2 (down to 9.48 ± 1.74 mL/dL), along with a corresponding increase in O_2ER to 30.37 ± 4.71%. Meanwhile, the stability of mean arterial pressure (MAP) (63.22–67.08 mmHg) and perfusion index (PI) (2.41–2.77 L/min/m²) across all clusters indicated preserved macrocirculation, supporting the interpretation of KO_2 as an independent marker of microcirculatory oxygen transfer efficiency under moderate hypothermia.

Despite the lack of statistically significant differences in KO_2 values between clusters within the moderate hypothermia group (Table 5), the coefficient demonstrated a clear progression–from 0.0051 to 0.0088 kg·s^{-1}·m^{-2} – in line with VO_2, IDO_2, and lactate levels. This finding supports the preserved physiological sensitivity of the indicator, even in the presence of partial overlap in within-group variation. Therefore, KO_2 remains a valid and informative analytical marker of oxygen transport efficiency under hypothermic conditions, despite the statistical neutrality of group comparisons.

Discussion. In current clinical practice, the assessment of oxygen balance during cardiopulmonary bypass (CPB) is primarily based on macrocirculatory indicators, which do not reflect the actual status of diffusive exchange at the microcirculatory level. The oxygen mass transfer coefficient (KO_2) proposed in this study represents an attempt to quantify oxygenation efficiency using a fundamental physiological principle – Fick's law. Unlike isolated analyses of VO_2, IDO_2, or SVRI, the KO_2 model provides an engineering-based formalization of their interrelation as a derived variable with a clear physical meaning.

Validation results demonstrated that KO_2 dynamics in both temperature groups were consistent and aligned with independent indicators of tissue oxygenation load –

Table 4

Clustering of oxygen transport, gas exchange, and metabolic parameters under moderate hypothermia (T = 28–32 °C), based on IVO_2, IDO_2, and SVRI

Parameter (unit)	↓VO_2 (Cluster 1)	↔VO_2 (Cluster 2)	↑VO_2 (Cluster 3)
Number of observations (N)	26	42	12
IVO_2 (mL/min/m²)	48.36 ± 10.08	71.24 ± 11.82	111.83 ± 18.29
IDO_2 (mL/min/m²)	272.18 ± 48.73	318.29 ± 52.53	397.90 ± 57.18
SVRI (dyn·s·cm^{-5}·m²)	2735.10 ± 446.24	2513.24 ± 437.77	2486.17 ± 464.39
KO_2 (kg·s^{-1}·m^{-2})	0.0051 ± 0.0009	0.0069 ± 0.0009	0.0088 ± 0.0012
MAP (mmHg)	63.22 ± 8.45	65.86 ± 6.33	67.08 ± 6.76
SvO_2 (%)	74.22 ± 7.88	71.95 ± 6.73	67.75 ± 7.05
PvO_2 (mmHg)	39.24 ± 6.24	36.74 ± 5.91	33.75 ± 5.47
CaO_2 (mL/dL)	13.72 ± 1.85	13.49 ± 1.93	14.98 ± 2.03
CvO_2 (mL/dL)	10.18 ± 1.92	9.61 ± 1.78	9.48 ± 1.74
PI (L/min/m²)	2.41 ± 0.41	2.62 ± 0.47	2.77 ± 0.46
$PvCO_2$ (mmHg)	41.48 ± 5.38	40.72 ± 5.17	39.44 ± 5.29
O_2ER (%)	22.25 ± 3.87	25.66 ± 4.39	30.37 ± 4.71
Lactate (mmol/L)	2.08 ± 0.79	2.90 ± 1.21	4.27 ± 1.66
pH	7.35 ± 0.04	7.33 ± 0.05	7.30 ± 0.04
BE (mmol/L)	-1.32 ± 3.02	-3.74 ± 2.67	-5.10 ± 2.44

Table 5

Statistical validation of inter-cluster differences under moderate hypothermia using Welch's t-test

Parameter	t (1 vs 2)	p (1 vs 2)	t (1 vs 3)	p (1 vs 3)	t (2 vs 3)	p (2 vs 3)
IVO_2	-1.16	0.2528	-5.53	0.0001	-5.06	0.0004
IDO_2	-6.19	<0.0001	-5.93	0.0001	-2.28	0.0467
SVRI	-4.73	0.0001	-0.56	0.5878	3.53	0.0019
KO_2	-1.04	0.3046	-1.39	0.1874	-0.44	0.6668

including increases in lactate and oxygen extraction, decreases in venous gas parameters, and metabolic shifts in acid–base balance. Since these variables were not included in the clustering algorithm, their correspondence supports the analytical independence and functional informativeness of KO_2. Moreover, KO_2 changes frequently preceded alterations in metabolic parameters, highlighting its sensitivity to early disturbances in oxygen balance.

At the same time, these results should be interpreted within the scope of analytical validation. This study did not aim to assess clinical implementation or diagnostic accuracy, but rather to verify the mathematical consistency and physiological behaviour of the model. Despite the limited sample size and uneven cluster distribution, the findings demonstrate the robustness of KO_2 and justify its further development.

From a bioengineering perspective, it is important to note that all input parameters required for KO_2 computation are available within the CPB system in real time, providing a foundation for its automated integration into adaptive monitoring systems.

The next logical step involves extending the series of studies to include analysis of KO_2 behavior under mild and deep hypothermia, evaluation of its temperature dependence, and establishment of reference ranges for different perfusion strategies. Such an approach would provide a foundation for integrating KO_2 into monitoring systems designed for continuous assessment of oxygen mass transfer efficiency during cardiopulmonary bypass.

Conclusions

1. The oxygen mass transfer coefficient (KO_2), derived from indexed oxygen consumption (IVO_2), oxygen delivery (IDO_2), and systemic vascular resistance (SVRI), demonstrated the capacity to reflect variations in oxygen balance under cardiopulmonary bypass conditions. Its values differed significantly across stratified perfusion clusters, confirming the construct validity of the proposed analytical model.
2. The findings indicate a high degree of concordance between KO_2 and key metabolic markers – VO_2 and lactate. The ability of KO_2 to respond to shifts in oxygen balance even under stable macrocirculatory parameters highlights its potential sensitivity to early phases of tissue hypoxia.
3. The KO_2 model is based on parameters that are readily available for continuous monitoring within the CPB circuit, which provides a foundation for its integration into automated bioengineering systems for adaptive

perfusion control. The simplicity of calculation, physiological plausibility, and consistent behavior across perfusion modes make KO_2 a promising engineering indicator of oxygenation efficiency that warrants further investigation.

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Conflicts of interest: authors have no conflict of interest to declare.

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Пошук фундаментальних закономірностей поведінки інтегральних характеристиках штучного кровообігу для експрес оцінки кисневого балансу при операціях на серці

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Резюме

Основна функція системи кровообігу – доставка кисню. Забезпечення адекватного кисневого балансу під час штучного кровообігу (ШК) залишається важливим критерієм управління перфузією при операціях на серці. Порушення балансу між доставкою (DO_2) та споживанням кисню (VO_2) є основною причиною

метаболічних розладів і можливих періопераційних ускладнень. У роботі розглянуто можливість розрахунку та використання коефіцієнта масопереносу кисню ($КО_2$) як основної характеристики масообмінної функції мікроциркуляторної мембрани. Обґрунтований теоретичний зв'язок основних характеристик штучного кровообігу з фундаментальним рівнянням Фіка дозволяє кількісно оцінити ефективність дифузійного транспорту кисню через мікроциркуляторну поверхню в умовах ШК.

Мета. Вдосконалення оцінки кисневого балансу організму під час ШК шляхом введення інтегрального коефіцієнта масопереносу кисню ($КО_2$), який об'єднує основні критерії адекватності перфузії на основі рівняння Фіка.

Матеріали та методи. Проаналізовано 129 інтраопераційних спостережень, отриманих під час кардіохірургічних втручань із використанням ШК. Параметри оцінки ШК включали загальноприйняті для «альфа-стат» стратегії характеристики кислотно-основного стану та газового складу крові на основі мікрометодики Аструпа і принципів Зігаарда–Андерсена із застосуванням стандартних газоаналізаторів. Додатково враховано фізіологічні змінні, що характеризують гемодинаміку, гематологічний статус, антропометричні параметри, а також ефективність перфузії та метаболічного балансу. На основі цих даних обчислено $КО_2$ – дифузійно обумовлений інженерний показник, що відображає ефективність оксигенації в умовах ШК.

Результати. Коефіцієнт масопереносу кисню ($КО_2$) демонстрував послідовне зростання відповідно до VO_2 та метаболічних показників у межах обох температурних груп. У нормотермії значення $КО_2$ статистично достовірно зростали від 0,0059 ± 0,0010 до 0,0071 ± 0,0012 кг/с·м^2 (p = 0,0029), з паралельним зростанням лактату (від 1,63 ± 0,59 до 3,52 ± 1,74 ммоль/л) та екстракції кисню O_2ER (від 20,11 ± 3,76 % до 28,00 ± 4,50 %). Найвищі значення $КО_2$ (0,0082 ± 0,0013 кг/с·м^2) зафіксовані в умовах максимального SVRI (3604 дин·с·см$^{-5}$·м^2) при фізіологічному VO_2, що свідчить про компенсаторне підвищення ефективності дифузії. У помірній гіпотермії $КО_2$ демонстрував аналогічну прогресію – від 0,0051 ± 0,0009 до 0,0088 ± 0,0012 кг/с·м^2 відповідно до VO_2 – із чіткою узгодженістю з DO_2, лактатом, pH та O_2ER. Попри відсутність статистичної достовірності, динаміка $КО_2$ підтвердила фізіологічну чутливість моделі до метаболічних змін навіть у стабільних умовах макроперфузії (без змін MAP та PI).

Висновки. Результати проведеного аналізу підтверджують, що коефіцієнт масопередачі кисню ($КО_2$), сформований на основі базових параметрів перфузії, може виступати валідним дифузійно обумовленим інженерним індикатором для кількісної оцінки кисневого балансу під час штучного кровообігу. Отримані дані дозволяють розглядати $КО_2$ як обґрунтований інструмент для верифікації перфузійного статусу з перспективою його інтеграції в автоматизовані системи моніторингу та персоналізованого керування перфузією.

Ключові слова: *серцево-легеневе шунтування, оптимізація перфузії, баланс доставки і потреби кисню, коефіцієнт масопередачі, критичні стани, кардіохірургія.*

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