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Original Article

Near-infrared spectroscopy and ultrasound as complementary methods for assessing organ and peripheral tissue perfusion in veno-arterial-ECMO patients

Li Zhang, Juan Wu, Xueli Ji, Xufeng Chen, Yong Mei, Xihua Huang

Department of Emergency Treatment, The First Affiliated Hospital of Nanjing Medical University, Nanjing 210000, Jiangsu, China

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Abstract: Background: Veno-arterial extracorporeal membrane oxygenation (VA-ECMO) is vital for stabilizing patients with severe cardiac and pulmonary failure. Effective management requires precise monitoring of organ perfusion and systemic physiologic status. Near-infrared spectroscopy (NIRS) and ultrasound (US) are emerging as key methods of assessment, but their combined utility remains underexplored in VA-ECMO patients. Methods: A retrospective analysis was conducted on 267 patients who received VA-ECMO between June 2018 and July 2023. Patients were divided into two groups based on weaning success, defined as survival for more than 48 hours post-weaning with improved cardiac function. Weaning trials involved incremental reductions in VA-ECMO flow, monitored by mean arterial pressure and other clinical measurements. Data including demographics, clinical scores [Glasgow Coma Scale (GCS), Acute Physiology and Chronic Health Evaluation II (APACHE II), Sequential Organ Failure Assessment (SOFA)], blood gas indicators, and NIRS and US metrics were collected and analyzed. Results: Significant differences were observed in cerebral regional oxygen saturation (rSO_2) dynamics and echocardiographic parameters between the groups. The successful group demonstrated higher maximal ΔrSO_2 (29.57% ± 13.77) than the failure group (25.86% ± 6.39, $P = 0.003$) and a lower minimal rSO_2 (40.67% ± 15.87 vs. 43.9% ± 4.27, $P = 0.010$). Post-ECMO, the successful group exhibited a higher cardiac index (CI, 2.47 L/min/m^2 ± 0.74) compared to the failure group (2.26 L/min/m^2 ± 0.61, $P = 0.018$). Pre-weaning, the successful group displayed lower left ventricular ejection fraction (LVEF, 32.06% ± 4.64) versus the failure group (34.55% ± 8.45, $P = 0.016$), yet post-weaning, it was higher (33.46% ± 4.85) than in the failure group (31.28% ± 7.37, $P = 0.017$). Additionally, the left ventricular outflow tract velocity-time integral (LVOT-VTI) pre-weaning was significantly lower in the successful group (14.95 cm ± 2.98) compared to the failure group (17.35 cm ± 7.22, $P = 0.006$). Conclusion: NIRS and US were found to beconsistent and complementary modalities for assessing perfusion and cardiac function in VA-ECMO patients.

Keywords: Extracorporeal membrane oxygenation, near-infrared spectroscopy, ultrasound, cardiac function, weaning strategies, cerebral oxygenation

Introduction

Veno-arterial extracorporeal membrane oxygenation (VA-ECMO) serves as a crucial life-support modality for patients experiencing severe cardiac and pulmonary failure, offering temporary stabilization by facilitating gas exchange and cardiac output [1]. While it provides critical support, VA-ECMO is not curative and poses significant risks, including complications due to hemodynamic fluctuations and organ perfusion inadequacies [2]. An essential component of successful VA-ECMO management is the accurate monitoring of organ perfusion and systemic physiologic status, which influences patient outcome and informs weaning strategies [3]. This demands the integration of reliable, precise, and minimally invasive monitoring techniques in clinical practice [4].

Near-infrared spectroscopy (NIRS) and ultrasound (US) have emerged as promising tools in this arena, capable of assessing cerebral and systemic perfusion, respectively [5]. Research highlights that the use of VA-ECMO can lead to hypoxic blood being delivered to the brain, coronary arteries, and upper limbs, thereby increasing the risk of ischemic injury in these areas.

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NIRS can be used to monitor regional oxygenation in the brain and tissues of patients undergoing VA-ECMO [6]. NIRS, a non-invasive modality, measures regional hemoglobin oxygen saturation (rSO_2), providing real-time data on cerebral oxygenation and perfusion dynamics [7]. Near-infrared spectroscopy may be a useful tool for monitoring hemodynamic stability during the early period of ECMO, while cerebral rSO_2 can predict in-hospital mortality after ECMO [8]. Given the brain's sensitivity to hypoxic conditions, NIRS can offer critical insight into cerebral perfusion adequacy and potential systemic perfusion challenges [9].

On the other hand, cardiac function determines circulatory dynamics, and parameters measured by US directly reflect cardiac pumping ability, guiding doctors in choosing the optimal timing for weaning from ECMO [10, 11]. Echocardiographic parameters could track the resolution of inadequate systemic perfusion and myocardial recovery, identifying patients who could successfully be weaned off ECMO [12]. US has been extensively used to evaluate cardiac function and hemodynamics, offering parameters such as left ventricular ejection fraction (LVEF), velocity-time integral (VTI), and cardiac index (CI), which are essential for assessing cardiac output and peripheral perfusion status [13, 14]. For instance, successful weaning patients have been shown to have lower LVEF compared to those who were not successfully weaned [15]. These measurements are particularly relevant in the VA-ECMO context, where cardiac output may fluctuate and affect systemic organ perfusion [16].

Currently, there have been numerous studies on the application of NIRS in monitoring cerebral oxygenation and US in assessing cardiac function. However, few studies have evaluated the combined use of both methods to assess perfusion in VA-ECMO patients. This study builds on this foundation, revealing significant differences in the indicators of both methods concerning successful versus unsuccessful weaning. This further clarifies the value of their combined reflection of the patient's overall perfusion status, providing strong evidence for clinical judgment on the timing of weaning. This has significant implications for improving the management of VA-ECMO patients.

Materials and methods

Ethics statement

The Institutional Review Board and Ethics Committee of our institution approved this study. Informed consent was waived because the research was retrospective and relied solely on deidentified patient data, ensuring no potential harm or impact on patient care. This waiver was granted in accordance with the regulatory and ethical guidelines governing retrospective research studies.

Study design

A retrospective analysis was performed on 267 patients who underwent VA-ECMO and were assessed using NIRS and US at our hospital between June 2018 and July 2023. Patients were categorized into two groups based on their ability to successfully wean from VA-ECMO. Successful weaning was defined as survival for more than 48 hours post-weaning, accompanied by improved cardiac function. Patients meeting the criteria for weaning (hemodynamic stability) underwent a weaning trial, during which the VA-ECMO flow was gradually decreased by 0.5 to 1.0 L/min increments. Patients were monitored for 15 minutes after each adjustment. If the mean arterial pressure (MAP) fell below 60 mmHg, the weaning trial was deemed unsuccessful. Weaning failure was also defined as not surviving for more than 48 hours post-weaning. Patients who successfully weaned (n = 189) were designated the successful group, while those who failed to wean (n = 78) comprised the failure group.

Inclusion and exclusion criteria

Inclusion criteria: successful implantation of VA-ECMO, aged 18 years or older, received VA-ECMO support for a minimum of 24 hours, and underwent NIRS and US monitoring during treatment. Additionally, only patients with complete and non-missing medical records were considered.

Exclusion criteria: Participants were excluded if they had a terminal malignancy, irreversible neurological injury, were pregnant or lactating, or had complications such as pneumothorax or congenital heart disease.

Data collection

Patient data, including general information, VA-ECMO indications, VA-ECMO parameters, blood gas indicators, and results from NIRS and US assessments, were collected by the medical record system. The Glasgow Coma Scale (GCS) was employed to evaluate patients' level of consciousness prior to intubation. The GCS assesses three components: eye opening response, verbal response, and motor response. The total score is the sum of these components. A score of 15 signifies full consciousness; scores between 13 and 15 indicate mild impairment; scores between 9 and 12 suggest moderate impairment; scores between 3 and 8 reflect severe impairment or coma; and a score below 3 may indicate brain death. Lower scores denote more severe levels of unconsciousness, whereas higher scores represent better levels of consciousness. The Cronbach's α coefficient for the GCS was 0.78, indicating acceptable reliability [17]. The Acute Physiology and Chronic Health Evaluation (APACHE II) score was utilized to assess patients' health status on the first day of VA-ECMO treatment. The APACHE II score comprises three components: the acute physiological score (APS), the age score, and the chronic health score. The overall APACHE II score is the sum of these components, with higher scores indicating more severe illness. The Cronbach's α coefficient for the APACHE II score was 0.76, reflecting an acceptable level of reliability [18]. The Sequential Organ Failure Assessment (SOFA) score was employed to evaluate the function of various organ systems during VA-ECMO treatment. This score assesses six organ systems: respiratory, cardiovascular, hepatic, renal, central nervous, and coagulation. The Cronbach's α coefficient for the SOFA score was 0.81, indicating good reliability [19].

Measurement of blood gas data

Upon admission, 5 mL of fasting arterial blood was collected from patients in the early morning. Blood gas data were measured using a blood gas analyzer (model ABL9, Suzhou Ledumei Medical Technology Co., Ltd.). The recorded data included pH, partial pressure of carbon dioxide (pCO_2), Bicarbonate levels ($pHCO_3$), partial pressure of oxygen (pO_2), and O_2 saturation. The collection was under aseptic conditions.

NIRS assessment method

Cerebral NIRS was utilized for all patients undergoing VA-ECMO. Cerebral oximetry measurements were conducted using the INVOS monitor (INVOS-5100C; Covidien; Mansfield, USA). Hourly regional hemoglobin oxygen saturation (rSO_2) values were collected in the ICU, beginning at the time of VA-ECMO cannulation. Data were simultaneously gathered for bilateral frontal cerebral rSO_2 using sensors placed on the forehead. For all patients, the data collected during the first seven days of VA-ECMO cannulation, or until cannulation ended if earlier, were recorded for analysis.

US assessment method

Echocardiographic examinations were conducted on all patients using a Mindray M9 US diagnostic system (Shenzhen Mindray Bio-Medical Electronics Co., Ltd.) equipped with a 1.0-5.0 MHz trans-thoracic US probe (model SP5-1s). The following parameters were recorded before treatment and on the third day of treatment: velocity-time integral variation index (ΔVTI), respiratory variation index (ΔRVI), central venous pressure (CVP), heart rate (HR), and CI. Additionally, LVEF, left ventricular outflow tract velocity-time integral (LVOT-VTI), and the velocity of the mitral annulus in systole (LatSa) were recorded both before weaning and within 12 hours post-weaning.

Statistical analysis

Data analysis was performed using SPSS 29.0 statistical software (SPSS Inc, Chicago, IL, USA). Categorical variables were expressed in the form of [n (%)] and analyzed using the chi-square test. The Shapiro-Wilk method was used to test the normality of continuous variables. For normally distributed continuous variables, data were presented as (Mean ± SD) and analyzed using the t-test with adjusted variance. A two-sided $P < 0.05$ was considered significant.

Results

Basic data

The mean age for the success and failure groups was 65.63 ± 8.43 years and 66.47 ± 8.13 years, respectively ($P = 0.459$) (**Table 1**). Gender distribution was similar, with females

Table 1. Comparison of general information between the two groups

	Successful group (n = 189)	Failure group (n = 78)	t/x^2	*P*
Age (years)	65.63 ± 8.43	66.47 ± 8.13	0.741	0.459
Female/Male	83 (43.92%)/106 (56.08%)	33 (42.31%)/45 (57.69%)	0.058	0.810
Body Mass Index (kg/m^2)	23.63 ± 2.42	24.13 ± 2.59	1.504	0.134
Smoking history	19 (10.05%)	8 (10.26%)	0.003	0.960
Drinking history	15 (7.94%)	7 (8.97%)	0.079	0.779
Hypertension	128 (67.72%)	49 (62.82%)	0.594	0.441
Hyperlipidemia	85 (44.97%)	33 (42.31%)	0.159	0.690
Diabetes	70 (37.04%)	26 (33.33%)	0.329	0.566
Ischemic Stroke	15 (7.94%)	8 (10.26%)	0.377	0.539
Intracranial Hemorrhage	0 (0%)	2 (2.56%)	2.043	0.153
Atrial Fibrillation	41 (21.69%)	23 (29.49%)	1.840	0.175
Educational level (high school or below/college or above)	24 (12.7%)/165 (87.3%)	12 (15.38%)/66 (84.62%)	0.342	0.559
Marital Status (Single/Married/Divorced)	68 (35.98%)/117 (61.9%)/4 (2.12%)	29 (37.18%)/46 (58.97%)/3 (3.85%)	0.730	0.694
Mechanical ventilation support time (h)	176.25 ± 19.43	181.65 ± 32.56	1.367	0.175
GCS	15.76 ± 3.64	16.45 ± 2.23	1.879	0.062

GCS: Glasgow coma scale immediately before cannulation.

Table 2. Comparison of VA-ECMO indication between the two groups of patients before and after intervention

	Successful group (n = 189)	Failure group (n = 78)	x^2	*P*
Post-Cardiotomy Shock	9 (4.76%)	5 (6.41%)	0.061	0.804
Cardiogenic Shock	39 (20.63%)	9 (11.54%)	3.098	0.078
ECPR	27 (14.29%)	18 (23.08%)	3.045	0.081
Cardiac arrest	0 (0%)	2 (2.56%)	2.043	0.153
Acute myocardial infarction	18 (9.52%)	7 (8.97%)	0.020	0.889
Arrhythmia	30 (15.87%)	7 (8.97%)	2.201	0.138
Acute Cardiopulmonary	15 (7.94%)	11 (14.1%)	2.388	0.122
Decompensation	15 (7.94%)	7 (8.97%)	0.079	0.779
Pulmonary Hypertension/Respiratory Insufficiency	17 (8.99%)	8 (10.26%)	0.104	0.748
Other	19 (10.05%)	4 (5.13%)	1.701	0.192

VA-ECMO: Veno-arterial extracorporeal membrane oxygenation; ECPR: extracorporeal cardiopulmonary resuscitation.

comprising 43.92% of the successful group and 42.31% of the failure group (*P* = 0.810). The body mass index was comparable between the groups (success: 23.63 ± 2.42 kg/m^2; failure: 24.13 ± 2.59 kg/m^2; *P* = 0.134). No significant differences were observed in smoking history (*P* = 0.960), drinking history (*P* = 0.779), hypertension (*P* = 0.441), hyperlipidemia (*P* = 0.690), diabetes (*P* = 0.566), ischemic stroke (*P* = 0.539), or intracranial hemorrhage (*P* = 0.153). The prevalence of atrial fibrillation was 21.69% in the successful group and 29.49% in the failure group (*P* = 0.175). Educational levels (*P* = 0.559) and marital status (*P* = 0.694) were similar between groups. Mechanical ventilation support times were 176.25 ± 19.43 hours for the success group and 181.65 ± 32.56 hours for the failure group (*P* = 0.175). Finally, the GCS scores were 15.76 ± 3.64 for the successful group and 16.45 ± 2.23 for the failure group (*P* = 0.062). Overall, the baseline characteristics between groups did not show statistical significance, suggesting homogeneity in the evaluated data.

VA-ECMO

The incidence of post-cardiotomy shock was 4.76% in the successful group and 6.41% in the failure group (*P* = 0.804) (**Table 2**). Cardiogenic shock was noted in 20.63% of the successfulgroup and 11.54% of the failure group (*P* = 0.078), while extracorporeal cardiopulmonary resuscitation (ECPR) was recorded in 14.29% and 23.08% of the successful and failure groups, respectively (*P* = 0.081). The incidence of cardiac arrest, although slightly higher in the failure group at 2.56%, compared to 0% in the successful group, was not significant (*P* = 0.153). Acute myocardial infarction occurred in 9.52% of the successful group 8.97% of the failure group (*P* = 0.889). Arrhythmias affected 15.87% of the successful group and 8.97% of the failure group (*P* = 0.138). Acute cardiopulmonary decompensation was observed in 7.94% of the successful group and 14.1% of the failure group (*P* = 0.122). Decompensation, pulmonary hypertension/respiratory insufficiency, and other indications were similarly distributed between groups, with no significant differences (*P* > 0.05 for all). The observed similarities in VA-ECMO indications suggest a comparable baseline presentation across both patient groups.

The duration of VA-ECMO support was similar, with the successful group at 6.37 ± 1.45 days and the failure group at 6.65 ± 1.65 days (*P* = 0.164) (**Table 3**). The SOFA score on VA-ECMO initiation was 13.79 ± 2.67 for the successful group versus 14.35 ± 3.63 for the failure group (*P* = 0.219). The APACHE II score on day one of VA-ECMO support showed no significant difference, with scores of 24.87 ± 6.28 for the successful group and 26.21 ± 6.25 for the failure group (*P* = 0.115). Central cannulation was performed in 38.62% of the successful group and 43.59% of the failure group (*P* = 0.452). Lastly, the VA-ECMO flow rates were 3.87 ± 0.58 LPM in the successful group and 4.01 ± 0.67 LPM in the failure group (*P* = 0.087). These findings suggest a comparable

Table 3. Comparison of VA-ECMO variables between two groups

	Successful group (n = 189)	Failure group (n = 78)	t	*P*
Duration of VA-ECMO Support (days)	6.37 ± 1.45	6.65 ± 1.65	1.395	0.164
SOFA score on VA-ECMO Day	13.79 ± 2.67	14.35 ± 3.63	1.236	0.219
APACHE II score on VA-ECMO Day 1	24.87 ± 6.28	26.21 ± 6.25	1.583	0.115
Central Cannulation	73 (38.62%)	34 (43.59%)	0.567	0.452
VA-ECMO Flow (LPM)	3.87 ± 0.58	4.01 ± 0.67	1.718	0.087

VA-ECMO: Veno-arterial extracorporeal membrane oxygenation; APACHE II: Acute Physiology and Chronic Health Evaluation II; SOFA: sequential organ failure assessment.

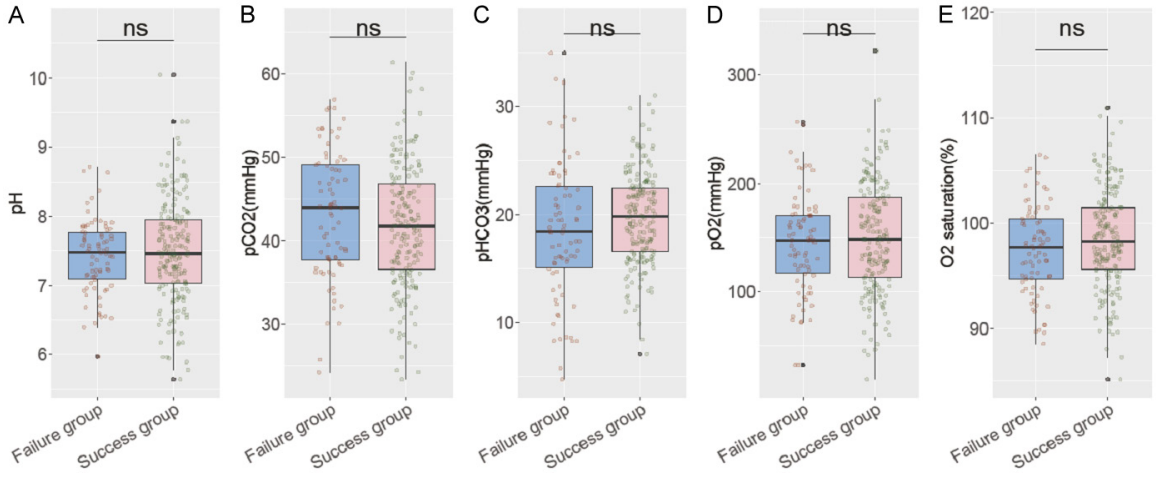

Figure 1. Comparison of blood gas indicators between two groups of diabetes patients. A: pH; B: Partial pressure of carbon dioxide (pCO_2) (mmHg); C: Bicarbonate levels ($pHCO_3$) (mmHg); D: Partial pressure of oxygen (pO_2) (mmHg); E: O_2 saturation (%).

application of VA-ECMO variables between the groups.

Blood gas indicators

The pH levels were 7.5 ± 0.75 in the successful group and 7.42 ± 0.54 in the failure group (*P* = 0.326). Partial pressure of carbon dioxide (pCO_2) measured 41.74 ± 7.39 mmHg for the successful group and 43.13 ± 7.55 mmHg for the failure group (*P* = 0.165) (**Figure 1**). Bicarbonate levels ($pHCO_3$) averaged 19.65 ± 4.27 mmHg in the successful group, compared to 18.43 ± 6.35 mmHg in the failure group (*P* = 0.124). The partial pressure of oxygen (pO_2) was 149.75 ± 50.66 mmHg in the successful group and 144.67 ± 46.25 mmHg in the failure group (*P* = 0.445). Oxygen saturation levels were similar, with the successful group at 98.54 ± 4.67% and the failure group at 97.45 ± 4.25% (*P* = 0.078). Overall, the blood gas indicators showed no significant differences between the two groups, indicating consistency in these data regardless of the outcome.

Results of NIRS assessment

Baseline rSO_2 was similar between groups, with the successful group at 55.25 ± 13.56% and the failure group at 57.13 ± 5.87% (*P* = 0.115), indicating no significant difference (**Figure 2**). However, the lowest rSO_2 values recorded were significantly different between the groups, with the successful group at 40.67 ± 15.87% compared to 43.9 ± 4.27% in the failure group (*P* = 0.010). Moreover, the maximal difference in cortical oxygen tissue saturation (ΔrSO_2) also showed a significant variation, with a mean of 29.57 ± 13.77% in the successful group and 25.86 ± 6.39% in the failure group (*P* = 0.003). These findings highlight significant differences in the minimal rSO_2 levels and the variability of rSO_2 between the two patient groups, suggesting that rSO_2 dynamics may be associated with outcomes in VA-ECMO patients.

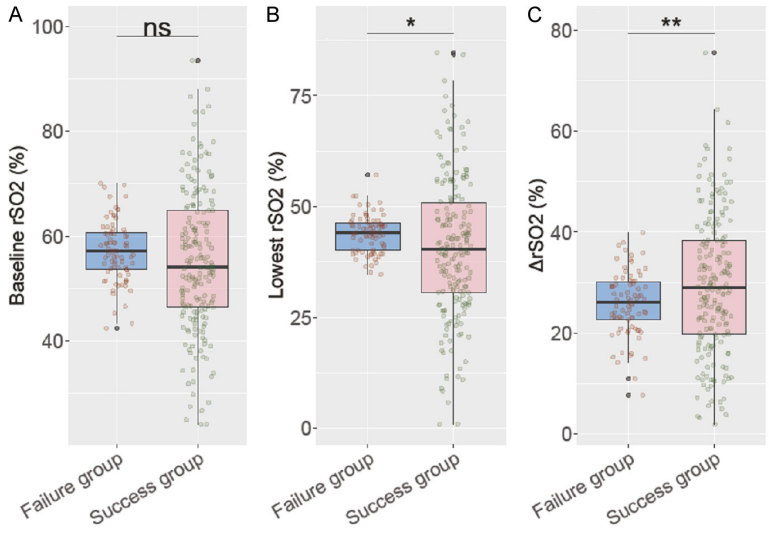

Figure 2. Comparison of rSO_2 content between two groups. A: Baseline rSO_2 (%); B: Lowest rSO_2 (%); C: ΔrSO_2 (%). rSO_2: cerebral regional oxygen saturation; ΔrSO_2: maximal diference between right and left cortical oxygen tissue saturation.

A drop of 20% from baseline was observed in 65.08% of the successful group and 65.38% of the failure group, with no significant difference (P = 0.962) (**Table 4**). However, a drop of 25% from baseline was significantly more prevalent in the failure group (65.38%) compared to the successful group (46.56%) (P = 0.005). Although not statistically significant, a drop of 30% from baseline occurred slightly more frequently in the failure group (57.69%) than in the successful group (46.56%) (P = 0.098). The proportion of patients with a minimum rSO_2 below 40% was similar between groups (P = 0.839). While the frequency of a minimum rSO_2 below 35% was higher in the failure group, this was not significant (P = 0.122). Notably, a minimum rSO_2 below 30% was significantly more common in the failure group (17.95%) than in the successful group (6.88%) (P = 0.006), as was a minimum rSO_2 below 25%, found in 15.38% of the failure group versus 6.88% of the successful group (P = 0.030). These results suggest that certain critical drops in rSO_2 are more associated with failure, indicating their potential role as predictive markers.

Results of US assessment

The respiratory variation index (ΔRVI) was 5.61 ± 1.23% in the successful group compared to 5.87 ± 1.47% in the failure group (P = 0.148) (**Figure 3**). The velocity-time integral variation index (ΔVTI) did not differ significantly, with values of 8.26 ± 1.78% for the successful group and 7.84 ± 2.22% for the failure group (P = 0.145). Central venous pressure (CVP) was 5.62 ± 2.67 mmH_2O in the successful group and 5.94 ± 2.17 mmH_2O in the failure group (P = 0.309). Heart rate (HR) was also comparable between groups, with means of 138.75 ± 13.77 bpm and 139.67 ± 12.97 bpm for the successful and failure groups, respectively (P = 0.614). The CI showed no significant difference, recorded at 1.78 ± 0.43 L/(min·m^2) in the successful group and 1.85 ± 0.56 L/(min·m^2) in the failure group (P = 0.319). These echocardiographic parameters suggest no significant pre-VA-ECMO hemodynamic differences between the two groups.

The respiratory variation index (ΔRVI) was significantly lower in the successful group (5.33 ± 0.78%) compared to the failure group (5.58 ± 0.57%) (P = 0.004) (**Figure 4**). Similarly, the velocity-time integral variation index (ΔVTI) was higher in the successful group (15.75 ± 2.43%) than in the failure group (14.24 ± 3.85%) (P = 0.002). Central venous pressure (CVP) values were similar between groups, with 8.38 ± 1.86 mmH_2O in the successful group and 8.56 ± 1.9 mmH_2O in the failure group, showing no significant difference (P = 0.468). Heart rate (HR) was also comparable, with the successful group at 105.88 ± 11.77 bpm and the failure group at 104.67 ± 14.67 bpm (P = 0.518). Notably, the CI was significantly higher in the successful group (2.47 ± 0.74 L/(min·m^2)) compared to the failure group (2.26 ± 0.61 L/(min·m^2)) (P = 0.018). These findings suggest that specific changes in echocardiographic parameters post-VA-ECMO may be indicative of patient outcomes, with higher ΔVTI and CI associated with success.

The LVEF was significantly lower in the successful group (32.06 ± 4.64%) compared to the failure group (34.55 ± 8.45%) (P = 0.016) (**Table 5**). The left ventricular outflow tract velocity

Table 4. Comparison of rSO_2 cutoff values between two groups

	Successful group (n = 189)	Failure group (n = 78)	x^2	*P*
Drop of 20% from Baseline	123 (65.08%)	51 (65.38%)	0.002	0.962
Drop of 25% from Baseline	88 (46.56%)	51 (65.38%)	7.839	0.005
Drop of 30% from Baseline	88 (46.56%)	45 (57.69%)	2.737	0.098
Minimum below 40%	75 (39.68%)	32 (41.03%)	0.041	0.839
Minimum below 35%	37 (19.58%)	22 (28.21%)	2.388	0.122
Minimum below 30%	13 (6.88%)	14 (17.95%)	7.444	0.006
Minimum below 25%	13 (6.88%)	12 (15.38%)	4.708	0.030

rSO_2: cerebral regional oxygen saturation.

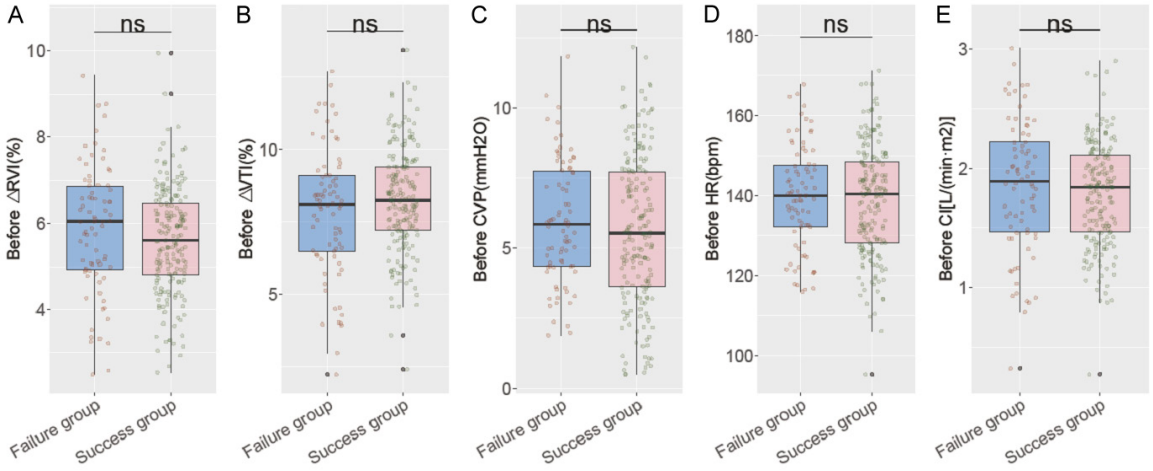

Figure 3. Comparison of echocardiographic parameters between the two groups (before VA-ECMO). A: ΔRVI (%); B: ΔVTI (%); C: CVP (mmH_2O); D: HR (bpm); E: CI [$L/(min{\cdot}m^2)$]. ΔRVI: respiratory variation index; ΔVTI: velocity-time integral variation index; CVP: central venous pressure; HR: heart rate; CI: cardiac index.

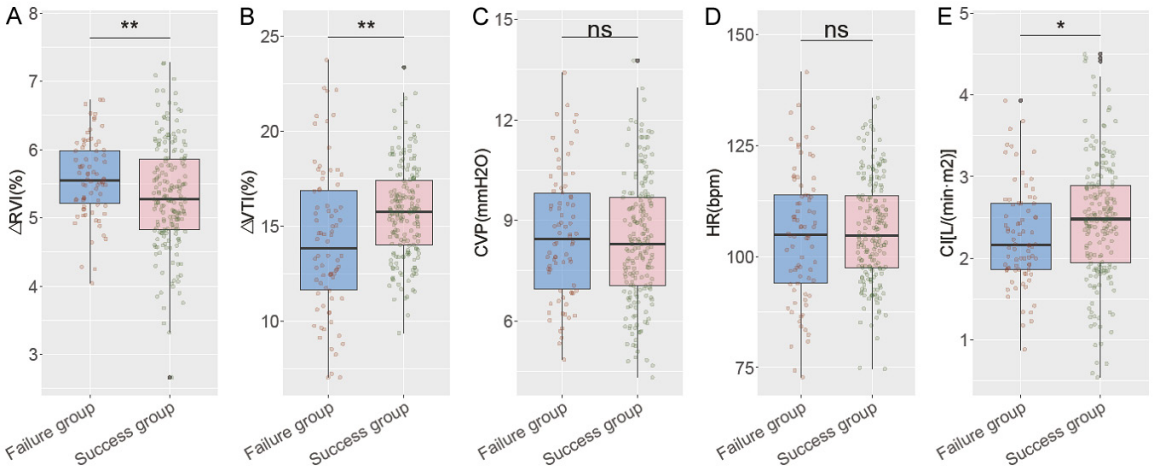

Figure 4. Comparison of echocardiographic parameters between the two groups (after VA-ECMO). A: ΔRVI (%); B: ΔVTI (%); C: CVP (mmH_2O); D: HR (bpm); E: CI [$L/(min{\cdot}m^2)$]. ΔRVI: respiratory variation index; ΔVTI: velocity-time integral variation index; CVP: central venous pressure; HR: heart rate; CI: cardiac index.

time integral (LVOT-VTI) was also significantly lower in the successful group (14.95 ± 2.98 cm) than in the failure group (17.35 ± 7.22 cm) (P = 0.006). Additionally, the velocity of the

Table 5. Comparison of US data between two groups (pre-weaning)

	Successful group (n = 189)	Failure group (n = 78)	t	*P*
LVEF (%)	32.06 ± 4.64	34.55 ± 8.45	2.458	0.016
LVOT-VTI (cm)	14.95 ± 2.98	17.35 ± 7.22	2.835	0.006
LatSa (cm/s)	4.25 ± 1.32	3.84 ± 0.98	2.810	0.005

US: ultrasound; LVEF: left ventricular ejection fraction; LVOT-VTI: left ventricular outflow tract velocity time integral; LatSa: velocity of mitral annulus in systole.

Table 6. Comparison of US data between two groups (within 12 h post-weaning)

	Successful group (n = 189)	Failure group (n = 78)	t	*P*
LVEF (%)	33.46 ± 4.85	31.28 ± 7.37	2.415	0.017
LVOT-VTI (cm)	15.07 ± 1.55	14.52 ± 1.68	2.548	0.011
LatSa (cm/s)	6.16 ± 1.34	5.53 ± 1.76	2.820	0.006

US: ultrasound; LVEF: left ventricular ejection fraction; LVOT-VTI: left ventricular outflow tract velocity time integral; LatSa: velocity of mitral annulus in systole.

mitral annulus in systole (LatSa) was higher in the successful group (4.25 ± 1.32 cm/s) compared to the failure group (3.84 ± 0.98 cm/s) (P = 0.005). These findings suggest that specific echocardiographic parameters, such as LVEF, LVOT-VTI, and LatSa, may be predictive of successful weaning from VA-ECMO.

The LVEF was significantly higher in the successful group (33.46 ± 4.85%) than in the failure group (31.28 ± 7.37%) (P = 0.017) (**Table 6**). Additionally, the left ventricular outflow tract velocity time integral (LVOT-VTI) was greater in the successful group (15.07 ± 1.55 cm) compared to the failure group (14.52 ± 1.68 cm) (P = 0.011). The velocity of the mitral annulus in systole (LatSa) was also significantly higher in the successful group (6.16 ± 1.34 cm/s) compared to the failure group (5.53 ± 1.76 cm/s) (P = 0.006). These results indicate that higher LVEF, LVOT-VTI, and LatSa values within 12 hours post-weaning were associated with successful weaning.

Discussion

In this study, we comprehensively examined the utility of NIRS and US assessments in veno-arterial extracorporeal membrane oxygenation (VA-ECMO) patients, evaluating their ability to consistently assess organ and peripheral tissue perfusion. VA-ECMO not only provides adequate oxygen supply but also partially replaces cardiac function, increasing systemic blood perfusion and maintaining sufficient cardiac output (CO), which aids in the recovery of cardiac function [20-22]. CO is a significant factor influencing cerebral blood flow (CBF). CBF depends on receiving a large portion of the blood pumped by the heart, and changes in CO can directly impact CBF [23]. The velocity of CBF and brain oxygenation are primarily associated with right ventricular function, indicating that rSO_2 dynamics can serve as a reliable tool for assessing cardiac and cerebral function [24, 25]. There is a complex interaction between brain oxygenation (rSO_2 dynamics) after ECMO and cardiac function. By monitoring changes in rSO_2 dynamics, we can gain deeper insight into the recovery of cardiac function, optimize ECMO treatment strategy, and provide a scientific basis for weaning decisions. This is crucial for improving patient outcome and reducing complications.

Regional cerebral tissue rSO_2, as one of the routine monitoring parameters, has been shown to be valuable in predicting mortality in pediatric ECMO patients in intensive care units, especially when rSO_2 < 60% with significant fluctuations [26]. Real-time monitoring of rSO_2 can detect hypoxia early, typically before it becomes apparent through conventional invasive hemodynamic monitoring, thereby allowing timely intervention to reduce organ damage [27]. This study found significant differences in the rSO_2 metrics measured by NIRS between the successful and unsuccessful weaning groups. The unsuccessful group exhibited lower minimum rSO_2 levels and higher ΔrSO_2, suggesting a close relationship between cerebral oxygenation and systemic perfusion. This may

be attributed to inadequate cardiac output or impaired autoregulatory mechanisms [28, 29]. Monitoring rSO_2 can help improve the success rate of weaning and reduce the occurrence of complications. This helps improve weaning success rate and reduce complications.

Consistent with the NIRS data, our US assessments highlighted key differences in cardiac and hemodynamic parameters between the two groups. The lower CI and LVEF recorded within the failure cohort post-VA-ECMO suggest that these patients were unable to generate adequate cardiac output, a factor crucial for maintaining systemic and cerebral perfusion [30, 31]. LVEF values in the successful weaning group were significantly higher than those in the failure weaning group, suggesting that higher LVEF was an important factor in predicting successful weaning of ECMO [32, 33]. In addition, the elevated respiratory variation index (ΔRVI) and reduced velocity-time integral variation index (ΔVTI) seen post-VA-ECMO in the failure group further affirm that respiratory and cardiac performance are less optimized in these patients.

Echo parameters such as LVOT-VTI and LatSa pre-and post-weaning provide additional insight into cardiac function during the weaning phase. These parameters are indicative of left ventricular outflow and mitral annular movement, respectively, and reflect systolic function [34, 35]. The failure group's significantly lower values suggest ongoing myocardial impairment or stress that prevents them from achieving hemodynamic stability off ECMO support [36]. As previous research has shown, when LVOT VTI exceeds 12.3 cm, it correlates positively with free survival after ECMO weaning. This suggests that LVOT-VTI is not only an effective tool for assessing left ventricular systolic function but also an important parameter for determining whether it is safe to discontinue ECMO support [37].

Blood gas analysis, while not demonstrative of significant differences between the groups regarding standard parameters like pH, pCO_2, pO_2, and $pHCO_3$, still offers valuable information. These indicators remained relatively stable, suggesting that while they are essential for physiological monitoring, they may not be sufficiently sensitive predictors of weaning, compared to dynamic metrics like NIRS and echocardiographic variables [38, 39]. The minimal but observed differences in oxygen saturation (between 98% in successes and 97% in failures) hint at subtle differences in oxygen delivery or utilization efficiency that might become more pronounced during the stress of weaning.

From a clinical perspective, these findings underscore the importance of comprehensive, multimodal monitoring of ECMO patients. The integration of NIRS and US presents a synergistic approach, allowing clinicians to gain a more holistic picture of a patient's physiologic status [40]. Real-time feedback on perfusion and cardiac function could better inform interventions aimed at optimizing patient stability, thus enabling more effective weaning strategies [41]. For instance, clinicians might prioritize interventions that target cardiac function improvement if US parameters consistently indicate suboptimal CI or ejection fraction.

In this study, a single-center retrospective study design was adopted, which has certain limitations. Since the data were extracted from existing medical records, there may have been selection bias. Additionally, the results of a single-center study are limited to a specific region, and the sample may lack representativeness due to patient individual differences (underlying diseases, age, etc.), differences in treatment processes (medications, ventilation settings, etc.), and healthcare environment factors (resource availability, medical staff proficiency). These possible confounding factors may have interfered with the association between NIRS, US indicators, and successful weaning from ECMO. For future studies, it is recommended to conduct prospective cohort studies or multicenter randomized controlled trials (RCTs), using randomization to control for confounding factors and increasing the sample size to enhance the reliability and scientific rigor of the findings.

Conclusion

This study illuminates the complex interplay of cerebral oxygen saturation, cardiac function, and systemic perfusion in the context of VA-ECMO. It establishes the potential for NIRS and US as valuable tools in assessing these parameters, promising an enhanced framework for patient management. Future research

should continue to refine these methods, ensuring that such technologies are leveraged to their fullest potential in critical care settings. This multi-faceted approach should contribute to improving VA-ECMO outcome, minimizing patient risk, and optimizing critical interventions.

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Disclosure of conflict of interest

None.

Address correspondence to: Xihua Huang, Department of Emergency Treatment, The First Affiliated Hospital of Nanjing Medical University, No. 300, Guangzhou Road, Gulou District, Nanjing 210000, Jiangsu, China. Tel: +86-13851525163; E-mail: huangxihualy@163.com

References

[1] Yannopoulos D, Bartos J, Raveendran G, Walser E, Connett J, Murray TA, Collins G, Zhang L, Kalra R, Kosmopoulos M, John R, Shaffer A, Frascone RJ, Wesley K, Conterato M, Biros M, Tolar J and Aufderheide TP. Advanced reperfusion strategies for patients with out-of-hospital cardiac arrest and refractory ventricular fibrillation (ARREST): a phase 2, single centre, open-label, randomised controlled trial. Lancet 2020; 396: 1807-1816.

[2] Wang R, Zhou M, Man Y, Zhu Y, Ding W, Liu Q, Sun B, Yan L, Zhang Y, Zhou H and Wang L. Lung ultrasound to evaluate pulmonary changes in patients with cardiogenic shock undergoing extracorporeal membrane oxygenation: a retrospective study. BMC Anesthesiol 2023; 23: 181.

[3] Krishnan S and Schmidt GA. Hemodynamic monitoring in the extracorporeal membrane oxygenation patient. Curr Opin Crit Care 2019; 25: 285-291.

[4] Douflé G, Dragoi L, Morales Castro D, Sato K, Donker DW, Aissaoui N, Fan E, Schaubroeck H, Price S, Fraser JF and Combes A. Head-to-toe bedside ultrasound for adult patients on extracorporeal membrane oxygenation. Intensive Care Med 2024; 50: 632-645.

[5] Su Y, Liu K, Zheng JL, Li X, Zhu DM, Zhang Y, Zhang YJ, Wang CS, Shi, TT, Luo Z and Tu GW. Hemodynamic monitoring in patients with venoarterial extracorporeal membrane oxygenation. Ann Transl Med 2020; 8: 792.

[6] Wong JK, Smith TN, Pitcher HT, Hirose H and Cavarocchi NC. Cerebral and lower limb near-infrared spectroscopy in adults on extracorporeal membrane oxygenation. Artif Organs 2012; 36: 659-667.

[7] Higami T, Kozawa S, Asada T, Obo H, Gan K, Iwahashi K and Nohara H. Retrograde cerebral perfusion versus selective cerebral perfusion as evaluated by cerebral oxygen saturation during aortic arch reconstruction. Ann Thorac Surg 1999; 67: 1091-1096.

[8] Zhang M, Yang Y, Chen X, Song Y, Zhu L, Gong X, Zhang H and Xu Z. Application of near-infrared spectroscopy to monitor perfusion during extracorporeal membrane oxygenation after pediatric heart surgery. Front Med (Lausanne) 2021; 8: 762731.

[9] Cruz SM, Akinkuotu AC, Rusin CG, Cass DL, Lee TC, Welty SE and Olutoye OO. A novel multimodal computational system using near-infrared spectroscopy to monitor cerebral oxygenation during assisted ventilation in CDH patients. J Pediatr Surg 2016; 51: 38-43.

[10] Kim D, Jang WJ, Park TK, Cho YH, Choi JO, Jeon ES and Yang JH. Echocardiographic predictors of successful extracorporeal membrane oxygenation weaning after refractory cardiogenic shock. J Am Soc Echocardiogr 2021; 34: 414-422.

[11] Sawada K, Kawakami S, Murata S, Nishimura K, Tahara Y, Hosoda H, Nakashima T, Kataoka Y, Asaumi Y, Noguchi T, Sugimachi M, Fujita T, Kobayashi J and Yasuda S. Predicting parameters for successful weaning from veno-arterial extracorporeal membrane oxygenation in cardiogenic shock. ESC Heart Fail 2021; 8: 471-480.

[12] Charbonneau F, Chahinian K, Bebawi E, Lavigueur O, Lévesque É, Lamarche Y, Serri K, Albert M, Noly PE, Cournoyer A and Cavayas YA. Parameters associated with successful weaning of veno-arterial extracorporeal membrane oxygenation: a systematic review. Crit Care 2022; 26: 375.

[13] Jentzer JC, Tabi M, Wiley BM, Lanspa MJ, Anavekar NS and Oh JK. Doppler-derived haemodynamics performed during admission echocardiography predict in-hospital mortality in cardiac intensive care unit patients. Eur Heart J Acute Cardiovasc Care 2022; 11: 640-650.

[14] Singh Y. Echocardiographic evaluation of hemodynamics in neonates and children. Front Pediatr 2017; 5: 201.

[15] Asaumi Y, Yasuda S, Morii I, Kakuchi H, Otsuka Y, Kawamura A, Sasako Y, Nakatani T, Nonogi H and Miyazaki S. Favourable clinical outcome

in patients with cardiogenic shock due to fulminant myocarditis supported by percutaneous extracorporeal membrane oxygenation. Eur Heart J 2005; 26: 2185-2192.
[16] Rozencwajg S, Guihot A, Franchineau G, Lescroat M, Bréchot N, Hékimian G, Lebreton G, Autran B, Luyt CE, Combes A and Schmidt M. Ultra-protective ventilation reduces biotrauma in patients on venovenous extracorporeal membrane oxygenation for severe acute respiratory distress syndrome. Crit Care Med 2019; 47: 1505-1512.
[17] Caruana M, Hackenbruch SN, Grech V and Farrugia R. Inconsistency in the application of glasgow coma scale in pediatric patients. Med Princ Pract 2024; 33: 41-46.
[18] Clark DO, Kroenke K, Callahan CM and McDonald CJ. Validity and utility of patient-reported health measures on hospital admission. J Clin Epidemiol 1999; 52: 65-71.
[19] Rhee C, Zhang Z, Kadri SS, Murphy DJ, Martin GS, Overton E, Seymour CW, Angus DC, Dantes R, Epstein L, Fram D, Schaaf R, Wang R and Klompas M; CDC Prevention Epicenters Program. Sepsis surveillance using adult sepsis events simplified eSOFA criteria versus sepsis-3 sequential organ failure assessment criteria. Crit Care Med 2019; 47: 307-314.
[20] Chen WY, Guo ZB, Kong TY, Chen WX, Chen XH, Yang Q, Wen YC, Wen QR, Zhou F, Xiong XM, Wen DL and Zhang ZH. ExtraCorporeal Membrane Oxygenation in the therapy for REfractory Septic shock with Cardiac function Under Estimated (ECMO-RESCUE): study protocol for a prospective, multicentre, non-randomised cohort study. BMJ Open 2024; 14: e079212.
[21] Premraj L, Brown A, Fraser JF, Pellegrino V, Pilcher D and Burrell A. Oxygenation during venoarterial extracorporeal membrane oxygenation: physiology, current evidence, and a pragmatic approach to oxygen titration. Crit Care Med 2024; 52: 637-648.
[22] Rao P, Khalpey Z, Smith R, Burkhoff D and Kociol RD. Venoarterial extracorporeal membrane oxygenation for cardiogenic shock and cardiac arrest. Circ Heart Fail 2018; 11: e004905.
[23] Meng L, Hou W, Chui J, Han R and Gelb AW. Cardiac output and cerebral blood flow: the integrated regulation of brain perfusion in adult humans. Anesthesiology 2015; 123: 1198-1208.
[24] Rodriguez MJ, Corredera A, Martinez-Orgado J and Arruza L. Cerebral blood flow velocity and oxygenation correlate predominantly with right ventricular function in cooled neonates with moderate-severe hypoxic-ischemic encephalopathy. Eur J Pediatr 2020; 179: 1609-1618.
[25] Tsaroucha A, Paraskeva A and Fassoulaki A. Measurements of oxygen saturation of brain, liver and heart areas in the supine and sitting position using near infrared spectrophotometry. Rom J Anaesth Intensive Care 2017; 24: 101-106.
[26] Chen S, Fang F, Liu W, Liu C and Xu F. Cerebral tissue regional oxygen saturation as a valuable monitoring parameter in pediatric patients undergoing extracorporeal membrane oxygenation. Front Pediatr 2021; 9: 669683.
[27] Yu LS, Chen XH, Zhou SJ, Zheng YR, Wang ZC and Chen Q. Using cerebral regional oxygen saturation and amplitude-integrated electroencephalography in neonates on extracorporeal membrane oxygenation: preliminary experience from a single center. BMC Pediatr 2024; 24: 590.
[28] Ostadal P, Rokyta R, Karasek J, Kruger A, Vondrakova D, Janotka M, Naar J, Smalcova J, Hubatova M, Hromadka M, Volovar S, Seyfrydova M, Jarkovsky J, Svoboda M, Linhart A and Belohlavek J; ECMO-CS Investigators. Extracorporeal membrane oxygenation in the therapy of cardiogenic shock: results of the ECMO-CS randomized clinical trial. Circulation 2023; 147: 454-464.
[29] Massol J, Simon-Tillaux N, Tohme J, Hariri G, Dureau P, Duceau B, Belin L, Hajage D, De Rycke Y, Charfeddine A, Lebreton G, Combes A and Bouglé A. Levosimendan in patients undergoing extracorporeal membrane oxygenation after cardiac surgery: an emulated target trial using observational data. Crit Care 2023; 27: 51.
[30] Li X, Wang L, Li C, Wang X, Hao X, Du Z, Xie H, Yang F, Wang H and Hou X. A nomogram to predict nosocomial infection in patients on venoarterial extracorporeal membrane oxygenation after cardiac surgery. Perfusion 2024; 39: 106-115.
[31] Li C, Wang H, Liu N, Jia M and Hou X. The effect of simultaneous renal replacement therapy on extracorporeal membrane oxygenation support for postcardiotomy patients with cardiogenic shock: a pilot randomized controlled trial. J Cardiothorac Vasc Anesth 2019; 33: 3063-3072.
[32] Cusanno A, Aissaoui N, Minville V, Porterie J, Biendel C, Volle K, Crognier L, Conil JM and Delmas C. Predictors of weaning failure in case of VA ECMO implantation. Sci Rep 2022; 12: 13842.
[33] Ye F, Yang Y, Liang Y and Liu J. Quantitative evaluation of hemodynamic parameters by echocardiography in patients with post-cardiotomy cardiac shock supported by extracorporeal membrane oxygenation. J Cardiothorac Surg 2023; 18: 1.

[34] Kim MC, Lim Y, Lee SH, Shin Y, Ahn JH, Hyun DY, Cho KH, Sim DS, Hong YJ, Kim JH, Jeong MH, Jung YH, Jeong IS and Ahn Y. Early left ventricular unloading after extracorporeal membrane oxygenation: rationale and design of EARLY-UNLOAD trial. ESC Heart Fail 2023; 10: 2672-2679.

[35] Kim MC, Lim Y, Lee SH, Shin Y, Ahn JH, Hyun DY, Cho KH, Sim DS, Hong YJ, Kim JH, Jeong MH, Jung YH, Jeong IS and Ahn Y. Early left ventricular unloading or conventional approach after venoarterial extracorporeal membrane oxygenation: the EARLY-UNLOAD randomized clinical trial. Circulation 2023; 148: 1570-1581.

[36] Jacquot A, Lepage X, Merckle L, Girerd N and Levy B. Protocol for a multicentre randomised controlled trial evaluating the effects of moderate hypothermia versus normothermia on mortality in patients with refractory cardiogenic shock rescued by venoarterial extracorporeal membrane oxygenation (VA-ECMO) (HYPO-ECMO study). BMJ open 2019; 9: e031697.

[37] Tavazzi G, Colombo CNJ, Klersy C, Dammassa V, Civardi L, Degani A, Biglia A, Via G, Camporotondo R, Pellegrini C and Price S. Echocardiographic parameters for weaning from extracorporeal membrane oxygenation - the role of longitudinal function and cardiac time intervals. Eur Heart J Cardiovasc Imaging 2025; 26: 359-367.

[38] Hayes K, Holland AE, Pellegrino VA, Young M, Paul E and Hodgson CL. Early rehabilitation during extracorporeal membrane oxygenation has minimal impact on physiological parameters: a pilot randomised controlled trial. Aust Crit Care 2021; 34: 217-225.

[39] Guervilly C, Fournier T, Chommeloux J, Arnaud L, Pinglis C, Baumstarck K, Boucekine M, Valera S, Sanz C, Adda M, Bobot M, Daviet F, Gragueb-Chatti I, Forel JM, Roch A, Hraiech S, Dignat-George F, Schmidt M, Lacroix R and Papazian L. Ultra-lung-protective ventilation and biotrauma in severe ARDS patients on veno-venous extracorporeal membrane oxygenation: a randomized controlled study. Crit Care 2022; 26: 383.

[40] Gannon WD, Stokes JW, Pugh ME, Bacchetta M, Benson C, Casey JD, Craig L, Semler MW, Shah AS, Troutt A and Rice TW. Simulation versus interactive mobile learning for teaching extracorporeal membrane oxygenation to clinicians: a randomized trial. Crit Care Med 2022; 50: e415-e425.

[41] Ellouze O, Nguyen M, Missaoui A, Berthoud V, Aho S, Bouchot O, Guinot PG and Bouhemad B. Prognosis value of early veno arterial PCO2 difference in patients under peripheral veno arterial extracorporeal membrane oxygenation. Shock 2020; 54: 744-750.