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URGENT LVAD IMPLANTATION IN CHILDREN ON PERIPHERAL VA-ECMO SUPPORT

V.N. Poptsov, D.V. Ryabtsev, E.A. Spirina, A.A. Kuznetsova, V.V. Kolyadina, A.Ch. Chartaev, A.S. Epremian, A.K. Solodovnikova, A.S. Ignatkina, Ya.S. Karina

Shumakov National Medical Research Center of Transplantology and Artificial Organs, Moscow, Russian Federation

Background. Heart transplantation (HT) remains the primary surgical treatment for children with end-stage chronic heart failure (CHF). More than 30% of pediatric HT candidates require short- or long-term mechanical circulatory support (MCS) due to refractoriness to medical therapy. In recent years, the use of left ventricular assist device (LVAD) systems has expanded not only in teenagers and middle-aged children but also in younger and smaller patients. **Objective:** to investigate the perioperative course of emergency LVAD implantation in children with critical hemodynamic compromise (INTERMACS profile I) requiring short-term MCS via peripheral veno-arterial extracorporeal membrane oxygenation (VA-ECMO). **Materials and methods.** We studied 25 patients under 18 years of age (12 girls, 48.0%; 13 boys, 52.0%) who had a HeartMate III LVAD LVAD implanted between January 1, 2021, and June 30, 2024. The severity of pre-implantation CHF was classified according to INTERMACS profiles: I (n = 4, 16.0%), II (n = 9, 36.0%), and III (n = 12, 48.0%). Patients were divided into two groups based on the need for VA-ECMO prior to LVAD implantation: the VA-ECMO–LVAD group (n = 4, 16.0%) and the LVAD group (n = 21, 84.0%). **Results.** The VA-ECMO–LVAD group (n = 4) did not differ significantly from the LVAD group (n = 21) in age, sex, or underlying disease. Intraoperatively, there were no significant differences between groups in the duration of cardiopulmonary bypass, doses of sympathomimetic cardiotonics, or the use of inhaled nitric oxide. The VA-ECMO–LVAD group showed a trend toward greater intraoperative blood loss and transfusion requirements ($p > 0.05$). In the postoperative period, blood loss volumes were similar between groups. However, patients in the VA-ECMO–LVAD group more frequently required re-sternotomy (25% *vs* 9.5%, $p < 0.05$), had a longer duration of postoperative mechanical ventilation (1.79-fold, $p < 0.05$), more often required renal replacement therapy (2.5-fold, $p = 0.166$), and had significantly longer ICU stays (2.75-fold, $p = 0.041$). In the VA-ECMO–LVAD group, the incidence of severe acute right ventricular dysfunction was significantly higher (25.0% *vs* 9.5%, $p = 0.016$). No significant difference in postoperative hospital mortality was observed between the two groups. **Conclusion.** Emergency implantation of an LVAD system in children with critical hemodynamic instability requiring preoperative short-term MCS using peripheral VA-ECMO has demonstrated high effectiveness. However, careful consideration should be given to the presence and severity of multiple organ dysfunction before and after LVAD implantation, as well as perioperative blood loss. These factors largely determine the anesthetic and resuscitative management strategies, as well as the immediate outcomes of long-term MCS.

Keywords: pediatric heart failure, heart transplantation, mechanical circulatory support, VA-ECMO, left ventricular assist device, right ventricular dysfunction.

INTRODUCTION

Heart transplantation (HT) remains the primary surgical treatment for children of various age groups with end-stage chronic heart failure (CHF) [1]. More than 30% of children who are candidates for HT require some form of mechanical circulatory support (MCS), either short-term or long-term, due to refractoriness to drug therapy [2]. The choice of MCS method in children depends on multiple factors, including the urgency of intervention, the type and severity of intracardiac hemodynamic disorders, the degree of organ dysfunction, and the child's anthropometric parameters [3]. In recent years, there has been a marked increase in the implantation of left ventricular assist device (LVAD) systems not only in adolescents and middle-aged children but also in younger and smaller patients [4, 5].

In children with severe systemic hemodynamic disorders, veno-arterial extracorporeal membrane oxygenation (VA-ECMO) with central or peripheral cannulation remains the most commonly used method of short-term MCS. This technique enables rapid restoration of hemodynamics and stabilization of the patient's clinical condition [6]. In both adults and children presenting with critical hemodynamic instability corresponding to INTERMACS level I, VA-ECMO serves as an effective bridge to long-term MCS, including implantable left

Corresponding author: Vitaly Poptsov. Address: 1, Shchukinskaya str., Moscow, 123182, Russian Federation. Phone: (963) 644-96-39. E-mail: poptsov_vit@mail.ru

ventricular assist devices (iLVAD), or to heart transplantation [7, 8]. However, emergency LVAD implantation in pediatric patients at INTERMACS level I who require preoperative VA-ECMO is associated with an increased risk of postoperative complications and adverse outcomes [9].

The aim of this study was to investigate the perioperative course of emergency LVAD implantation in children with critical hemodynamic instability requiring pre-implantation peripheral VA-ECMO (pVA-ECMO) support (INTERMACS profile I).

MATERIALS AND METHODS

The study included 25 patients (<18 years of age), comprising 12 girls (48.0%) and 13 boys (52.0%), who had an LVAD implanted between 2021 and June 30, 2024. In all cases, the HeartMate III LVAD system was used. The age of the patients ranged from 5 to 17 years (mean 11.0 ± 3.5; median 11.5 [8.8; 14.0] years). Nine patients (36.0%) were between 5–10 years old, and sixteen (64.0%) were between 11–17 years old. Body weight ranged from 14.2 to 91 kg (mean 39.5 ± 20.2; median 34.5 [25.0; 54.0] kg), with 60% (n = 15) weighing less than 40 kg. Height ranged from 115 to 187 cm (mean 150.3 ± 23.2; median 154.0 [129.5; 163.5] cm), and 32% (n = 8) were shorter than 130 cm. Body surface area (BSA) ranged from 0.64 to 2.17 m^2 (mean 1.30 ± 0.47 m^2), with 56% (n = 14) having a BSA below 1.3 m^2. Body mass index (BMI) ranged from 10.4 to 26.2 kg/m^2 (mean 18.2 ± 5.1 kg/m^2).

The underlying cardiac pathologies leading to CHF were as follows: dilated cardiomyopathy in 22 patients (88.0%), hypertrophic cardiomyopathy in 2 (8.0%), and restrictive cardiomyopathy in 1 (4.0%).

The severity of pre-implantation CHF was classified according to the INTERMACS profiles: profile I in 4 patients (16.0%), profile II in 9 (36.0%), and profile III in 12 (48.0%).

In 4 patients (16.0%), 2 girls and 2 boys aged 12–14 years (mean 13.0 ± 0.8), pVA-ECMO was used prior to LVAD implantation due to critical systemic hemodynamic disorders (INTERMACS profile I).

All patients (n = 25) were divided into two study groups based on the need for pVA-ECMO before LVAD implantation: the VAECMO–LVAD group (n = 4, 16.0%) and the LVAD group (n = 21, 84.0%). A comparative analysis was conducted to evaluate differences in pre-implantation status, intraoperative parameters, and early postoperative outcomes between the two groups.

Data collection, statistical processing, and comparative analysis were performed using Microsoft Excel and IBM SPSS Statistics software. Quantitative variables were expressed as mean ± standard deviation (M ± SD) for normally distributed data or as median and interquartile range (Me [Q1; Q3]) for non-normally distributed data. The Student's t-test or Mann–Whitney U test was applied for comparison of continuous variables, depending on data distribution. Categorical variables were presented as numbers (n) and percentages (%) of the number of observations. For small sample sizes, quantitative observations were analyzed using Fisher's exact test.

STUDY RESULTS

The VA-ECMO–LVAD group (n = 4; 16.0%) did not differ significantly from the LVAD group (n = 21; 84.0%) in terms of age, sex, or underlying disease (Table 1). In both groups, the proportion of female patients was approximately 50%.

Patients in the VA-ECMO–LVAD group had significantly greater height, weight, BMI, and BSA compared with those in the LVAD group. Consistent with the critical nature of their pre-implantation condition, these patients also exhibited more severe manifestations of CHF, as reflected by a higher NYHA functional class: 4.0 ± 0.0 in the VA-ECMO–LVAD group versus 3.2 ± 0.7 in the LVAD group (p = 0.01).

In three of the four patients in the VA-ECMO–LVAD group, cannulation and connection to the pVA-ECMO circuit were performed in the operating room, while in one patient, these procedures were carried out in the intensive care unit during cardiopulmonary resuscitation (CPR). In this case, restoration of spontaneous cardiac activity and systemic hemodynamics was achieved only after initiation of extracorporeal support. The interval between the onset of conventional CPR and start of extracorporeal CPR was 24 minutes.

Prior to initiation of pVA-ECMO, systemic and central hemodynamic parameters in these patients (n = 4) were as follows: mean arterial pressure (mAP) – 49.2 ± 5.3 mmHg, central venous pressure (CVP) – 14.5 ± 4.9 mmHg, mean pulmonary artery pressure (mPAP) – 35.8 ± 12.7 mmHg, pulmonary artery wedge pressure (PAWP) – 27.8 ± 9.8 mmHg, and cardiac index (CI) – 1.46 ± 0.3 L/min/m^2. All patients required cardiotonic therapy, including dopamine (7.4 ± 2.1 μg/kg/min, n = 3), dobutamine (5.8 μg/kg/min, n = 1), and adrenaline (40.8 ± 11.8 ng/kg/min, n = 3).

Before initiation of short-term MCS, echocardiographic assessment showed a right ventricular size of 2.9 ± 0.5 cm, left ventricular end-diastolic volume (LVEDV) of 223.5 ± 38.3 mL, and left ventricular ejection fraction (LVEF) of 21.3 ± 7.2%. Laboratory parameters were as follows: pH – 7.301 ± 0.08, base excess (BEb) – –4.5 ± 0.7 mmol/L, blood lactate – 4.9 ± 1.4 mmol/L, urea – 9.9 ± 8.4 (7.4 [5.41; 11.9]) mmol/L, creatinine – 62.8 ± 40.2 (57.9 [33.9; 126.65]) μmol/L, total bilirubin – 84.8 ± 49.8 (84.6 [38.23; 100.5]) μmol/L, ALT – 502.6 ± 583.0 (300.5 [153.5; 649.0]) U/L, AST – 104.7 ± 47.6 (95.5 [80.75; 112.75]) U/L, and INR – 2.04 ± 0.22 (1.90 [1.93; 2.06]).

The duration of pVA-ECMO before LVAD implantation was 3.8 ± 0.9 days, with an extracorporeal blood

flow rate of 3.2 ± 0.9 L/min, or 1.8 ± 0.4 L/min/m^2. Before LVAD implantation, total bilirubin decreased to 69.6 ± 38.5 (69.15 [38.23; 100.5]) μmol/L (p = 0.648), ALT to 308.2 ± 370.0 (183.45 [89.18; 402.55]) U/L (p = 0.746), and AST to 68.8 ± 26.8 (62.10 [50.40; 80.44]) U/L (p = 0.241). A downward trend was also observed in international normalized ratio (INR) values to 1.71 ± 0.21 (1.65 [1.58; 1.78]) (p = 0.073), although these changes were not statistically significant.

In the LVAD-only group, 10 (47.6%) of 21 patients required intravenous cardiotonic therapy prior to implantation. Dopamine was administered in 6 patients (28.6%) at dosages of 2–12 μg/kg/min (mean 4.3 ± 3.9; median 3.0 [2.0; 4.0] μg/kg/min), and dobutamine in 4 patients (19.0%) at dosages of 1–5 μg/kg/min (mean 3.2 ± 1.8; median 3.0 [2.25; 4.0] μg/kg/min). The duration of preimplantation cardiotonic therapy ranged from 1–16 days, averaging 3.7 ± 1.9 days (median 2.75 [2.0; 5.0]).

Table 1

Demographic, anthropometric, and clinical characteristics of children before implantation of a left ventricular assist device (n = 25)

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
Count (n)	4	21	
Age, years M ± o Me [Q1; Q3]	 13.0 ± 0.8 13.0 [12.75; 13.25]	 10.6 ± 3.7 11.0 [7.0; 14.0]	0.253
Female n/%	 2/50.0	 10/47.6	1.0
Height, cm M ± o Me [Q1; Q3]	 171.3 ± 15.2 172.5 [162.0; 181.75]	 142.8 ± 20.5 144.0 [128.0; 158.0]	0.025
Weight, kg M ± o Me [Q1; Q3]	 68.3 ± 21.2 69.0 [54.5; 82.75]	 34.1 ± 15.1 32.0 [21.0; 38.0]	0.004
BMI, kg/m^2 M ± o Me [Q1; Q3]	 22.7 ± 3.3 23.0 [20.7; 25.0]	 15.5 ± 3.7 14.6 [12.9; 16.4]	0.006
Body surface area, m^2 M ± o Me [Q1; Q3]	 1.80 ± 0.36 1.80 [1.57; 2.04]	 1.17 ± 0.33 1.20 [0.89; 1.35]	0.008
Heart disease: DCM, n/% HCM, n/% RCM, n/% Other, n/%	 4/100 0/0.0 0/0.0 0/0.0	 17/80.9 1/4.8 1/4.8 2/9.5	1.00
Chronic HF severity (Strazhesko–Vasilenko classification) Stage IIa, n/% Stage IIb, n/% Stage 3, n/%	 0/0.0 1/25.0 3/75.0 0/	 6/2.8.6 11/52.4 4/19.0	
NYHA functional classification III IV M ± o Me [Q1; Q3]	 0/0.0 4/100 4.0 ± 0.0 0/0.0	 16/76.2 5/23.8 3.1 ± 0.7 0/0.0	0.010
INTERMACS, level I, n/% II, n/% III, n/% IV, n/% M ± o Me [Q1; Q3]	 4/100 0/0.0 0/0.0 0/0.0 4.0 ± 0.0 4.0 [4.0; 4.0]	 0/0.0 10/47.6 10/47.6 1/4.8 2.6 ± 0.6 3.0 [2.0; 3.0]	 <0.0001

Abbreviations: VA-ECMO, veno-arterial extracorporeal membrane oxygenation; LVAD, left ventricular assist device; BMI, body mass index; DCM, dilated cardiomyopathy; HCM, hypertrophic cardiomyopathy; RCM, restrictive cardiomyopathy; HF, heart failure; NYHA, New York Heart Association; INTERMACS, Interagency Registry for Mechanically Assisted Circulatory Support.

A comparative analysis of the pre-implantation status of patients in both groups revealed no statistically significant intergroup differences in central or systemic hemodynamic parameters (Table 2). However, patients in the VA-ECMO–LVAD group showed significantly lower levels of hemoglobin, erythrocytes, thrombocytes, and lactate in mixed venous blood, accompanied by significantly higher levels of leukocytes, total bilirubin, ALT, AST, and INR prior to LVAD implantation.

LVAD implantation was performed in all patients under cardiopulmonary bypass (CPB) conditions. The two groups did not differ significantly in CPB duration, doses of sympathomimetic cardiotonics, or the need for intraoperative inhaled nitric oxide therapy (Table 3). However, patients in the VA-ECMO–LVAD group exhibited a greater, though not statistically significant ($p > 0.05$), intraoperative blood loss and higher transfusion volumes.

Analysis of the postoperative period revealed that, despite the absence of differences in postoperative blood loss, patients in the VA-ECMO–LVAD group more often required re-sternotomy (25% vs. 9.5%, $p < 0.05$), had a 1.79-fold longer duration of postoperative mechanical ventilation ($p < 0.05$), a 2.5-fold higher need for renal replacement therapy ($p = 0.166$), and a 2.75-fold longer ICU stay ($p = 0.041$) compared with the LVAD group (Table 4).

In the VA-ECMO–LVAD group, the incidence of severe acute right ventricular failure (ARVF) was significantly higher compared with the LVAD group (25.0% vs. 9.5%, $p = 0.016$).

Table 2

Laboratory and biochemical parameters of children before implantation of a left ventricular bypass system (n = 25)

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
Count (n)	4	21	
mAP, mmHg M ± o Me [Q1; Q3]	 69.8.0 ± 5.3 69.5 [66.25; 73.0]	 66.0 ± 12.1 66.0 [62.0; 70.0]	0.548
HR, in min M ± o Me [Q1; Q3]	 127.0 ± 43.0 133.5 [106.25; 154.25]	 94.5 ± 21.5 95.0 [86.0; 106.0]	0.028
RAP, mmHg M ± o Me [Q1; Q3]	 7.3 ± 5.0 7.5 [4.50; 11.25]	 9.8 ± 4.7 9.0 [8.0; 11.0]	0.344
mPAP, mmHg M ± o Me [Q1; Q3]	 28.2 ± 19.0 25.0 [23.0; 34.75]	 30.4 ± 13.3 25.0 [20.0; 38.0]	0.853
PCWP, mmHg M ± o Me [Q1; Q3]	 19.5 ± 10.1 17.0 [15.5; 26.0]	 22.1 ± 9.3 20.0 [16.0; 27.0]	0.675
TPG, mmHg M ± o Me [Q1; Q3]	 8.7 ± 4.5 9.5 [6.5; 11.45]	 8.3 ± 5.8 6.0 [5.0; 11.0]	0.767
CI M ± o Me [Q1; Q3]	 1.86 ± 0.98 1.64 [1.16; 2.38]	 1.91 ± 0.55 1.9 [1.60; 2.60]	0.850
PVR, Wood's unit M ± o Me [Q1; Q3]	 2.61 ± 1.26 2.56 [1.50; 3.88]	 3.74 ± 2.38 2.71 [1.73; 6.23]	0.208
Hemoglobin, g/L M ± o Me [Q1; Q3]	 97.8 ± 9.4 96.0 [91.25; 102.5]	 122.1 ± 14.7 122.0 [111.0; 133.0]	0.004
RBC, $\times 10^{12}$/L M ± o Me [Q1; Q3]	 3.71 ± 0.93 3.52 [3.33; 3.91]	 4.47 ± 0.54 4.60 [4.13; 4.80]	0.030
WBC, $\times 10^{9}$/L M ± o Me [Q1; Q3]	 12.5 ± 4.3 12.0 [9.58; 14.88]	 7.94 ± 1.85 7.70 [6.40; 9.10]	0.019
Platelets, $\times 10^{9}$/L M ± o Me [Q1; Q3]	 94.0 ± 60.3 100.5 [59.0; 135.50]	 285.1 ± 89.1 284.0 [202.0; 344.0]	0.0002

End of Table 2

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
Urea, mmol/L M ± o Me [Q1; Q3]	 9.9 ± 8.4 7.40 [5.41; 11.88]	 7.8 ± 3.8 7.10 [4.99; 9.02]	0.344
Creatinine, μmol/L M ± o Me [Q1; Q3]	 62.8 ± 40.2 57.88 [83.99; 86.65]	 53.3 ± 10.7 52.00 [48.6; 60.7]	0.334
Total bilirubin, μmol/L M ± o Me [Q1; Q3]	 69.6 ± 38.5 69.15 [38.23; 100.5]	 18.7 ± 7.4 16.38 [13.20; 24.23]	0.002
ALT, U/L M ± o Me [Q1; Q3]	 308.2 ± 370 183.45 [89.18; 402.55]	 52.7 ± 100.0 22.3 [10.3; 31.6]	0.0044
AST, U/L M ± o Me [Q1; Q3]	 68.8 ± 26.8 62.10 [50.40; 80.44]	 58.8 ± 66.5 33.0 [25.19; 47.0]	0.081
Total protein, g/L M ± o Me [Q1; Q3]	 65.1 ± 4.3 66.25 [53.88; 67.45]	 69.0 ± 7.5 70.0 [63.40; 76.30]	0.236
INR M ± o Me [Q1; Q3]	 1.71 ± 0.21 1.65 [1.58; 1.78]	 1.41 ± 0.46 1.30 [1.10; 1.15]	0.029
pH (venous) M ± o Me [Q1; Q3]	 7.38 ± 0.08 7.40 [7.30; 7.40]	 7.37 ± 0.08 7.40 [7.30; 7.42]	0.821
Base excess (BE), mmol/L M ± o Me [Q1; Q3]	 –0.31 ± 2.66 –0.30 [–0.95; 1.15]	 0.65 ± 3.65 1.10 [–2.03; 3.73]	0.624
Sodium (Na), mmol/L M ± o Me [Q1; Q3]	 138.8 ± 8.4 136.0 [135.00; 139.75]	 135.9 ± 3.4 136.0 [134.00; 137.00]	0.85
Lactate, mmol/L M ± o Me [Q1; Q3]	 1.50 ± 0.57 1.30 [1.10; 1.70]	 1.05 ± 0.37 1.0 [0.80; 1.10]	0.041
PvO_2, mmHg M ± o Me [Q1; Q3]	 39.4 ± 6.4 39.00 [35.15; 43.25]	 36.7 ± 5.9 35.6 [36.50; 44.00]	0.543
SvO_2, % M ± o Me [Q1; Q3]	 70.05 ± 5.82 69.25 [65.35; 73.95]	 61.39 ± 9.61 59.40 [54.80; 64.90]	0.045

Abbreviations: VA-ECMO, veno-arterial extracorporeal membrane oxygenation; LVAD, left ventricular assist device; mAP, mean arterial pressure; HR, heart rate; RAP, right atrial pressure; mPAP, mean pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; TPG, transpulmonary gradient; CI, cardiac index; PVR, pulmonary vascular resistance; RBC, red blood cells; WBC, white blood cells; ALT, alanine aminotransferase; AST, aspartate aminotransferase; INR, international normalized ratio; PvO_2, mixed venous partial pressure of oxygen; SvO_2, mixed venous oxygen saturation.

Table 3

Intraoperative parameters in children undergoing LVAD implantation (n = 25)

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
Count (n)	4	21	
CPB duration M ± o Me [Q1; Q3]	 80.5 ± 18.0 75.0 [67.0; 88.50]	 87.9 ± 42.6 78.0 [69.00; 90.00]	0.739
Intraoperative blood loss, mL M ± o Me [Q1; Q3]	 1375.0 ± 914.2 1200.0 [800.0; 1775.0]	 605.3 ± 624.7 400.0 [300.0; 700.0]	0.046

End of Table 3

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
RBC transfusion n/% mL	4/100 692.5 ± 167.4 650.0 [607.50; 735.00]	13/61.9 422.4 ± 149.1 340.0 [310.0; 602.5]	0.001
FFP transfusion, n/% mL	4/100 1102.5 ± 347.6 1230.0 [1005.0; 1327.5]	21/100 767.7 ± 264.8 760.0 [570.0; 1000.0]	0.001
Platelet transfusion n/% mL	3/75.0 276.7 ± 40.4 300.0 [265.0; 300.0]	4/19.0 185.0 ± 69.5 185.0 [127.5; 242.5]	0.019
iNO therapy n/% ppm	4/100 17.5 ± 5.0 20.0 [17.5; 20.0]	12/57.1 20.3 ± 6.9 20.0 [19.28; 20.00]	0.260
Adrenaline (end of surgery) n/% mcg/kg/min	3/75.0 30.0 ± 10.0 30.0 [25.0; 35.0]	8/38.1 28.9 ± 23.7 20.0 [10.0; 40.0]	0.288 0.929
Dopamine (end of surgery) n/% mcg/kg/min	4/100 5.8 ± 0.5 6.0 [5.75; 6.00]	12/57.1 4.6 ± 2.4 4.0 [4.0; 4.0]	0.260 0.337
Dobutamine (end of surgery) n/% mcg/kg/min	1/25 2.0	7/33.1 4.1 ± 2.3 20.0 [10.0; 40.0]	0.267

Abbreviations: VA-ECMO, veno-arterial extracorporeal membrane oxygenation; LVAD, left ventricular assist device; CPB, cardiopulmonary bypass; RBC, red blood cell; FFP, fresh frozen plasma; iNO, inhaled nitric oxide.

Table 4

Postoperative parameters in children after LVAD implantation (n = 25)

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
Count (n)	4	21	
Resternotomy n/%	1/25	2/9.5	0.016
Blood loss, mL M ± o Me [Q1; Q3]	400.0 ± 173.2 300.00 [300.00; 375.00]	397.9 ± 164.9 320.00 [300.00; 500.00]	0.991
Mechanical ventilation, hours M ± o Me [Q1; Q3]	21.3 ± 13.1 17.50 [6.25; 27.0]	11.89 ± 7.2 7.0 [5.0; 19.0]	0.047
Adrenaline therapy, days M ± o Me [Q1; Q3]	5.0 ± 4.2 3.0 [2.50; 5.50]	4.2 ± 2.9 3.5 [2.0; 5.75]	0.641
Right ventricular bypass n/%	1/25	2/9.5	0.016
RRT (CVVHDF) n/%	2/50	3/14.3	0.166
WBC (max), $\times 10^9$/L M ± o Me [Q1; Q3]	18.9 ± 9.6 16.00 [14.55; 19.75]	16.1 ± 5.6 16.5 [13.05; 19.45]	0.421
Platelets (min), $\times 10^9$/L M ± o Me [Q1; Q3]	55.0 ± 52.4 77.0 [33.5; 115.25]	108.6 ± 43.1 40.0 [52.5; 133.50]	0.027

End of Table 4

Indicator	Patient group		p-value
	VA-ECMO–LVAD	LVAD	
Hemoglobin (Hb), g/dL M ± o Me [Q1; Q3]	 7.8 ± 0.8 8.30 [7.68; 8.70]	 8.1 ± 0.9 7.8 [7.4; 8.60]	0.542
Urea (max), mmol/L M ± o Me [Q1; Q3]	 19.4 ± 5.4 17.60 [11.53; 22.50]	 10.6 ± 6.9 9.40 [6.71; 15.85]	0.025
Creatinine (max), μmol/L M ± o Me [Q1; Q3]	 92.7 ± 24.8 78.5 [65.89; 91.75]	 68.9 ± 20.4 68.0 [49.15; 83.85]	0.049
Total bilirubin (max), μmol/L M ± o Me [Q1; Q3]	 108.0 ± 41.5 87.00 [59.60; 117.75]	 51.9 ± 41.0 46.10 [21.55; 71.50]	0.020
ALT (max), U/L M ± o Me [Q1; Q3]	 418.9 ± 380.2 180.2 [68.99; 446.2]	 128.6 ± 218.9 41.3 [27.15; 125.50]	0.041
AST (max), U/L M ± o Me [Q1; Q3]	 109.7 ± 62.6 109.9 [79.0; 147.09]	 127.6 ± 79.7 135.1 [79.40; 200.85]	0.677
Total protein (min), g/L M ± o Me [Q1; Q3]	 59.7 ± 3.2 59.00 [56.74; 61.25]	 62.6 ± 6.5 60.0 [55.93; 64.65]	0.398
INR (max) M ± o Me [Q1; Q3]	 2.17 ± 0.56 1.80 [1.48; 2.25]	 1.70 ± 0.35 1.60 [1.50; 2.00]	0.035
ICU stay, days M ± o Me [Q1; Q3]	 10.8 ± 4.4 11.00 [7.50; 14.25]	 5.3 ± 4.7 4.0 [2.00; 6.00]	0.041
In-hospital mortality n/%	0/0.0	3/14.3	1.000

Abbreviations: ALV, artificial ventilation of the lungs; RRT, renal replacement therapy; CVVHDF, continuous venovenous hemodiafiltration; WBC, white blood cells; ALT, alanine aminotransferase; AST, aspartate aminotransferase; INR, international normalized ratio; ICU, intensive care unit.

This hemodynamic complication developed in one patient in the VA-ECMO–LVAD group. To ensure adequate LVAD performance, the patient was transitioned from pVA-ECMO to a transcutaneous paracorporeal right ventricular assist circuit using the right femoral vein–right internal jugular vein configuration, with return cannulation into the pulmonary artery according to the previously described technique [10]. ARVD also occurred in two patients in the LVAD group. In the first case, transcutaneous paracorporeal right ventricular bypass was performed, while in the second case – due to the child's small anthropometric parameters – a paracorporeal right ventricular bypass with central cannulation was used, following the right atrium–pulmonary artery configuration. Patients in the VA-ECMO–LVAD group showed more pronounced clinical and laboratory signs of hepatorenal syndrome in the postoperative period. However, no significant differences in in-hospital postoperative mortality were observed between the groups.

DISCUSSION

Implantable LVADs have become an increasingly popular method of long-term MCS not only in adults but also in children. This trend is largely driven by continuous technological advancements, including device miniaturization, enhanced hemocompatibility, and improved thromboresistant properties, which collectively allow for a reduction in the intensity of anticoagulant and antiplatelet therapy. These improvements have contributed to a lower incidence of thrombotic and hemorrhagic complications, as well as a prolonged duration of assisted circulation [11].

According to the Pedimacs international registry (2024, 2025), implantable LVADs are now the leading modality of long-term MCS in pediatric patients, accounting for approximately 37–39% of all cases [12, 13]. The introduction of the HeartWare® Ventricular Assist Device (HVAD) into clinical practice has further expanded the feasibility of long-term MCS in children with smaller anthropometric parameters [14]. Notably, growing clinical experience has demonstrated the safety and efficacy

of LVAD implantation in children with a body surface area below 1.3 m^2 [15].

Many factors determine the immediate and long-term outcomes of LVAD implantation, including the severity of preimplantation CHF, degree of organ dysfunction, and urgency with which MCS is initiated [16]. The optimal timing for LVAD implantation in patients with CHF is before the onset of cardiogenic shock or acute decompensation of CHF [17]. Nevertheless, in about half of patients, the preimplantation hemodynamic status corresponds to INTERMACS profiles I–II [18]. The appropriateness of LVAD implantation in patients with critical hemodynamic disorders (cardiogenic shock, acute decompensation of CHF) remains a subject of debate, as these patients have increased risk of intraoperative and early postoperative complications [19], including right ventricular dysfunction, cerebrovascular and infectious events, pump thrombosis, and hemolysis [17]. Importantly, the clinical efficacy of LVAD support is significantly lower in patients presenting with preimplantation multiple dysfunction, primarily liver dysfunction/insufficiency arising from severe decompensated CHF [20].

Prior to LVAD implantation, 51–87% of patients with hemodynamic profiles corresponding to INTERMACS level I require pVA-ECMO. This intervention is indicated in cases of cardiogenic shock and/or life-threatening cardiac arrhythmias refractory to antiarrhythmic therapy [21, 22]. The principal causes of such severe preimplantation hemodynamic compromise in patients with an INTERMACS profile I classification are acute myocardial infarction, decompensated ischemic or dilated cardiomyopathy, and acute myocarditis [22].

According to H.-Y. Fu et al. (2023), emergency LVAD implantation in children (median age, 9.6 years) was required in 72.7% of cases, with 66.7% of all patients – and 91.7% of those with an INTERMACS I profile – receiving preimplantation VA-ECMO support [23]. LVAD implantation in patients presenting with cardiogenic shock but without prior short-term MCS is associated with high early postoperative mortality (23.8–28.6%) [24, 25]. Therefore, LVAD implantation should be performed before the onset of cardiogenic shock and severe impairment of organ perfusion, whereas patients with critical hemodynamic instability should undergo implantation following prior short-term MCS [26].

Short-term MCS prior to LVAD implantation enhances hemodynamic stability, restores organ perfusion, and mitigates multiple organ dysfunction, thereby improving the outcomes of subsequent long-term MCS [27, 28]. Several modalities of short-term MCS are used in pediatric patients, with the choice determined by the nature and severity of central hemodynamic impairment and the patient's anthropometric characteristics [29]. Among these, VA-ECMO with central or peripheral cannulation is the most widely employed, including in the pre-LVAD period [31, 32]. VA-ECMO provides both hemodynamic and respiratory support, particularly in the presence of pulmonary gas exchange disorders secondary to cardiogenic shock [27]. The use of VA-ECMO as the primary method of extracorporeal life support (ELS) in critical hemodynamic states has enabled the implementation of the concepts of MCS continuity ("bridge-to-bridge") and treatment optimization ("bridge-to-decision") [33]. For prolonged pre-implantation MCS, lasting up to a month or more, mono- or biventricular bypass with central cannulation using the CentriMag perfusion system based on magnetic levitation technology is employed [34].

Acute ischemic injury leading to renal ("shock kidney") and hepatic ("shock liver") dysfunction is a strong predictor of mortality following LVAD implantation [35]. LVAD implantation is contraindicated in patients with severe hyperbilirubinemia resulting from irreversible ischemic injury to the biliary epithelium and shock-induced secondary sclerosing cholangitis. Acute ischemic renal injury is associated with a high incidence (up to 45.5%) of renal replacement therapy (RRT) during the early postoperative period in patients who received pre-implantation short-term MCS. In our study, RRT was required 3.5 times more frequently after LVAD implantation in children who underwent pre-implantation VA-ECMO compared with those without prior MCS (50% vs. 14.3%). Nevertheless, pre-implantation VA-ECMO in patients with critical hemodynamic compromise is regarded as an important strategy to prevent the progression of renal failure in the post-implantation period [36].

Both in our study and in reports by other authors, the use of VA-ECMO prior to LVAD implantation contributed to improved systemic hemodynamics (increased mAP and decreased CVP) and enhanced organ function, as reflected by reductions in total bilirubin, serum creatinine, and hepatic transaminases (ALT, AST) by the time of LVAD implantation [21]. In our study, the duration of pre-implantation VA-ECMO support ranged from 1 to 16 days, with a mean of 3.7 ± 4.9 (1.00 [1.00; 5.00]) days. In other studies, the interval between initiation of short-term MCS and subsequent LVAD implantation averaged 4–7 days, which was attributed to the need for more sustained regression of multiple organ dysfunction [22].

D. Schibisky et al. (2017) reported that in 93.3% of patients receiving short-term MCS prior to LVAD implantation, the pre-implantation clinical status improved to INTERMACS level III TCS (temporary circulatory support) with VA-ECMO use [22]. Similarly, J.B. Durinka et al. (2014) recommended continuing short-term MCS until full normalization of organ function, with a median duration of 12.1 days [37]. However, other studies have highlighted the negative impact of prolonged pre-implantation VA-ECMO on LVAD outcomes. D. Tsyganenko et al. (2019) showed that VA-ECMO exceeding 7 days prior to LVAD implantation is an independent predictor of mortality in patients subsequently receiving long-term MCS [38]. Mortality among pati-

ents with LVADs was 9.4 times higher (75% vs. 8%) when VA-ECMO was used for more than 14 days before implantation, compared with shorter durations of pre-implantation support [37].

Volumetric overload of the left ventricle in the setting of progressive systolic dysfunction is one of the recognized complications of short-term MCS using the VA-ECMO method prior to LVAD implantation. This condition may necessitate surgical interventions aimed at unloading the left heart chambers. For this purpose, an additional drainage cannula can be inserted either through a minithoracotomy or by percutaneous transseptal puncture [39]. In the latter case, the resulting atrial septal defect is subsequently closed after LVAD implantation by percutaneous insertion of an intracardiac occluder.

The incidence of multiple organ failure (renal and/or hepatic dysfunction), as well as hemorrhagic and infectious complications (leukocytosis, pneumonia, bacteremia), following LVAD implantation is higher in patients who required pre-implantation VA-ECMO. This is attributed not only to the specific characteristics of this short-term MCS method but also to more severe preoperative disturbances in hemodynamics, hemostasis, and organ function [39]. Decreased hemoglobin and platelet levels during VA-ECMO increase the risk of hemorrhagic complications and contribute to greater intraoperative blood loss during subsequent LVAD implantation [39]. Consistent with previous studies [5], our findings demonstrated increased intraoperative blood loss, higher rates of re-sternotomy, and greater transfusion requirements in patients with pre-implantation VA-ECMO. These factors may explain the longer duration of postoperative mechanical ventilation and ICU stay observed in this subgroup of patients with implantable LVAD.

Acute right ventricular failure (ARVF) develops in 6–40% of patients after LVAD implantation. This complication occurs more frequently in patients presenting with pre-implantation cardiogenic shock and is associated with several factors, including hemodynamic instability, elevated CVP, dependence on cardiotonic and vasopressor support, and the need for mechanical ventilation. In cases of severe hemodynamic compromise due to ARVF developing against the background of left ventricular failure, temporary paracorporeal right ventricular bypass or continuation of pre-implantation VA-ECMO in the early post-implantation period is indicated [22, 36].

The use of VA-ECMO before LVAD implantation helps to prevent post-implantation ARVF by improving systemic hemodynamics, reducing elevated CVP, and facilitating weaning from mechanical ventilation to spontaneous breathing. Given the high risk of ARVF in patients with INTERMACS profile I, several studies recommend maintaining VA-ECMO support for the first four days after LVAD implantation [36]. In our study, severe ARVF developed significantly more often in the VA-ECMO–LVAD group, which may be related to the shorter duration of VA-ECMO use prior to LVAD implantation compared with other reports. We believe that paracorporeal right ventricular bypass represents a more effective MCS method for ARVF occurring after LVAD implantation, as it provides superior hemodynamic conditions for optimal LVAD performance.

In the absence of recovery of right ventricular function sufficient to ensure adequate LVAD performance, urgent heart transplantation is indicated [42]. Delayed initiation of right ventricular bypass adversely affects not only the outcomes of LVAD implantation but also those of subsequent urgent heart transplantation in cases of irreversible right ventricular dysfunction [43].

Our study did not reveal a negative impact of urgent LVAD implantation or pre-implantation VA-ECMO use on the immediate outcomes of long-term MCS in children.

CONCLUSION

Our experience confirms the high efficacy of urgent left ventricular assist device implantation in pediatric patients with critical hemodynamic instability requiring preoperative short-term mechanical circulatory support using peripheral veno-arterial extracorporeal membrane oxygenation. The presence and severity of multiple organ dysfunction, both before and after LVAD implantation, as well as the extent of perioperative blood loss, must be carefully considered, as these factors critically influence anesthetic management, postoperative intensive care strategies, and the immediate outcomes of long-term mechanical circulatory support.

The authors declare no conflict of interest.

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