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Combined Left Ventricular Assist Device and Temporary Right Ventricular Assist Device for End-Stage Heart Failure of Different Etiologies: A Case Series and Analysis of Perioperative Management Strategies

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Case Report

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Abstract

Approximately one-third of patients with end-stage heart failure present with concomitant biventricular dysfunction. Left ventricular assist device (LVAD) implantation has become a critical salvage therapy for advanced heart failure. However, for patients with severe preoperative right ventricular dysfunction, isolated LVAD implantation carries an extremely high risk of refractory postoperative right heart failure, which significantly increases perioperative mortality. Currently, clinical data regarding the combined use of the domestic Corheart 6 magnetically levitated LVAD and extracorporeal temporary right ventricular assist device (temporary RVAD) for end-stage heart failure of different etiologies remain limited.

This retrospective case series analyzed the clinical data of 2 patients with end-stage heart failure at our center. One patient had ischemic cardiomyopathy with multi-vessel coronary artery disease and underwent concomitant coronary artery bypass grafting during surgery; the other had dilated cardiomyopathy complicated with chronic renal insufficiency. Both patients presented with severe preoperative right ventricular dysfunction. After multidisciplinary discussion, all patients underwent Corheart 6 LVAD implantation combined with extracorporeal magnetically levitated temporary RVAD (Extra-VAD; Xinqing Medical, China) under general anesthesia with cardiopulmonary bypass. This paper summarizes the preoperative evaluation, surgical strategies, device parameter settings, and perioperative management experience of the two cases.

The results showed that both operations were completed successfully. The temporary RVAD was successfully weaned off on postoperative day 7 and day 4, respectively. Perioperative complications were effectively controlled with symptomatic management, and both patients were discharged in recovered condition on postoperative day 40 and day 50, respectively. At the 2-month postoperative follow-up, both patients had stable hemodynamics, significantly improved cardiac function and quality of life, and no thrombosis, bleeding, or device-related complications.

This preliminary case series suggests that concomitant LVAD and temporary RVAD implantation is a safe and feasible option for selected patients with end-stage heart failure of different etiologies complicated with high-risk right ventricular dysfunction. Precise volume management, individualized anticoagulation, and etiology-based perioperative strategies may contribute to improved prognosis. Given the small sample size of only 2 cases, the generalizability of the findings is limited, and further validation in large multicenter cohorts is warranted.

1. Introduction

Patients with end-stage heart failure present with critical illness, markedly reduced exercise tolerance, poor quality of life, and high mortality, with limited efficacy of conventional medical therapy. Heart transplantation remains the gold standard for treatment, but its clinical application is severely limited by the critical shortage of donor hearts. Therefore, ventricular assist devices have become the core modality of mechanical circulatory support for end-stage heart failure.

Right heart failure is a common complication of end-stage heart failure, with 30% of patients reported to have concomitant biventricular dysfunction, and it is also one of the most serious postoperative complications after LVAD implantation [1]. Chronic left heart failure often masks underlying right ventricular dysfunction. After LVAD implantation, increased left cardiac output leads to a sudden surge in venous return, which can rapidly aggravate right heart failure [2]. For patients with right heart failure that cannot be corrected after volume optimization and inotropic therapy, temporary or permanent RVAD implantation is required [3]. For high-risk patients with confirmed severe right ventricular dysfunction preoperatively, concomitant biventricular circulatory support is recommended [2,4].

Currently, there is no dedicated assist device fully adapted to the anatomical and physiological characteristics of the right heart. The domestic third-generation fully magnetically levitated Corheart 6 LVAD (Corheart 6; Levitas Bio, China) has the advantages of small size and favorable hemocompatibility, and has been widely used in clinical practice [5]. The extracorporeal magnetically levitated temporary RVAD (Extra-VAD) has the advantages of reversibility, minimal invasiveness, and ease of management, and can serve as an effective bridging strategy for right ventricular function recovery [4].

Ischemic cardiomyopathy and dilated cardiomyopathy are the two leading etiologies of end-stage heart failure, with significant differences in pathophysiological mechanisms, characteristics of right ventricular injury, and perioperative management between the two. However, there are few domestic comparative case reports on concomitant LVAD combined with temporary RVAD in patients with these two etiologies.

Since the initiation of mechanical circulatory support therapy at our center, we have successfully treated multiple patients with end-stage heart failure using the Corheart 6 LVAD. Among them, 2 patients with severe right ventricular dysfunction of different etiologies received concomitant temporary RVAD implantation, with effective correction of hemodynamics. This study retrospectively analyzed the clinical data of these 2 patients, and summarized the experience in preoperative evaluation, surgical strategies, device parameter matching, and complication management, so as to provide a reference for the clinical management of similar cases.

2. Case Presentation

2.1 Case 1: Ischemic Cardiomyopathy

A 66-year-old Han Chinese male, with a height of 170 cm, body weight of 55 kg, body surface area (BSA) of 1.61 m^2, and body mass index (BMI) of 19.0 kg/m^2, was admitted to our hospital. He had a long-term history of smoking and alcohol consumption, as well as a history of coronary heart disease. There was no family history of cardiomyopathy, and no underlying diseases such as hypertension or diabetes mellitus.

The patient developed exertional dyspnea and chest tightness 2 years prior, without standardized diagnosis and treatment. His symptoms aggravated 2 weeks before admission, accompanied by bilateral lower extremity edema and cough. He was diagnosed with heart failure at an external hospital,

with temporary relief of symptoms after medical therapy. During this period, he developed drug-induced liver injury secondary to prior medical therapy, and transaminase levels decreased after hepatoprotective treatment. He presented with sudden dyspnea 1 day before admission, was diagnosed with acute decompensated heart failure, and was transferred to our hospital via the emergency department.

On admission, physical examination showed a significantly enlarged cardiac dullness border and grade Ⅲ pansystolic murmur at the apex. Laboratory tests revealed elevated white blood cell count and inflammatory markers, hepatorenal insufficiency, and a marked increase in B-type natriuretic peptide (BNP). Electrocardiography showed paroxysmal supraventricular tachycardia and T-wave changes in leads Ⅰ, aVL, V5 to V6. Echocardiography showed biventricular dilatation, left ventricular end-diastolic diameter (LVEDD) of 66 mm, left ventricular ejection fraction (LVEF) of 20%, impaired right ventricular systolic function, tricuspid annular plane systolic excursion (TAPSE) of 11 mm, pulmonary artery systolic pressure (PASP) of 53 mmHg, and moderate mitral and tricuspid regurgitation.

Chest computed tomography (CT) showed emphysema, bilateral pneumonia, and pleural effusion. Cardiac magnetic resonance (CMR) showed subendocardial myocardial infarction with LVEF of 17%, right ventricular ejection fraction (RVEF) of 22%, right ventricular end-diastolic diameter of 42 mm, and diffuse hypokinesis of the right ventricular free wall, indicating severe right ventricular systolic dysfunction. Right heart catheterization showed low cardiac output, moderate pulmonary hypertension, elevated systemic and pulmonary vascular resistance, and normal volume load. Coronary angiography revealed severe stenosis of multiple vessels: 60% stenosis at the distal end of the left main coronary artery, 80% stenosis with severe calcification in the proximal segment of the left anterior descending artery, 70% stenosis in the intermediate branch, 80% stenosis in the distal segment of the left circumflex artery, and 80% stenosis in the proximal segment of the right coronary artery.

The patient was diagnosed with: (1) ischemic cardiomyopathy with biventricular involvement; (2) end-stage heart failure (acute decompensation), New York Heart Association (NYHA) functional class Ⅳ, Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) profile 3 (stable inotrope-dependent); (3) multi-vessel coronary atherosclerotic heart disease; (4) moderate regurgitation of both atrioventricular valves; (5) pulmonary hypertension; (6) hepatorenal insufficiency. Preoperative risk stratification using the Michigan Right Ventricular Failure Risk Score yielded a total score of 7, indicating high risk of postoperative right heart failure (score ≥ 6 defines high risk).

Preoperatively, the patient received optimized therapy for 1 week, including inotropic support with levosimendan, high-dose diuresis, and anti-infective therapy. Follow-up echocardiography showed slight improvement in right ventricular function and significant improvement in liver and kidney function, but persistent biventricular dilatation and valvular regurgitation. Given that the patient's hemodynamics stabilized with medical optimization and did not progress to cardiogenic shock, preoperative temporary left-sided mechanical circulatory support (such as Impella or intra-aortic balloon pump) was not indicated. In addition, preoperative percutaneous device implantation would increase the risk of

puncture-site bleeding and vascular complications in a patient scheduled for concomitant coronary artery bypass grafting, with limited incremental benefit for right heart optimization.

2.2 Case 2: Dilated Cardiomyopathy

A 45-year-old Han Chinese male, with a height of 172 cm, body weight of 87 kg, BSA of 2.08 m², and BMI of 29.41 kg/m², was admitted to our hospital. He had a history of chronic nephritis, and no history of hypertension, diabetes mellitus, smoking, alcohol consumption, or family history of cardiomyopathy. He developed exertional chest tightness and shortness of breath 7 years prior, and was diagnosed with heart failure at an external hospital, with poor response to regular medical therapy. He presented with orthopnea and severe bilateral lower extremity edema 1 week before admission, and was transferred to our hospital after ineffective symptomatic treatment.

On admission, physical examination showed a significantly enlarged cardiac dullness border and grade □ pansystolic murmur at the apex. Laboratory tests showed renal insufficiency and BNP > 5000 pg/mL. Echocardiography showed global cardiac dilatation, LVEDD of 79 mm, LVEF of 21%, TAPSE of 11 mm, PASP of 48 mmHg, diffuse hypokinesis of bilateral ventricular walls, and moderate regurgitation of both atrioventricular valves. Coronary CT angiography showed no significant stenosis, ruling out ischemic cardiomyopathy.

CMR showed diffuse myocardial fibrosis with LVEF of 5%, RVEF of 18%, right ventricular end-diastolic volume index (RVEDVI) of 128 mL/m², and significant right ventricular remodeling, consistent with severe right ventricular systolic dysfunction in dilated cardiomyopathy. Right heart catheterization showed low cardiac output, severe pulmonary hypertension, excessive volume load, and normal pulmonary vascular resistance (PVR).

The patient was diagnosed with: (1) dilated cardiomyopathy with biventricular involvement; (2) end-stage heart failure, acute decompensation, NYHA functional class □, INTERMACS profile 2 (progressive decline); (3) severe pulmonary hypertension; (4) chronic kidney disease with acute kidney injury. Preoperative Michigan Right Ventricular Failure Risk Score was 11, indicating very high risk of postoperative right heart failure.

After admission, the patient received inotropic therapy with dopamine combined with levosimendan and high-dose diuresis, with no significant improvement in urine output and progressive increase in serum creatinine. On day 5 after admission, he developed oliguria and profuse sweating with acute decompensated heart failure, and was transferred to the intensive care unit (ICU) for comprehensive treatment including non-invasive ventilation, continuous renal replacement therapy (CRRT), and diuresis with recombinant human brain natriuretic peptide.

The core pathophysiological abnormality in this patient was severe right heart dysfunction combined with volume overload. Left-sided temporary mechanical circulatory support devices only improve left-sided forward flow and have limited effect on right ventricular contractility and right-sided preload. Therefore, CRRT for volume removal and internal environment correction was selected as the primary

preoperative optimization strategy for right heart failure, rather than left-sided mechanical circulatory support. After preoperative optimized therapy, the internal environment was stable, and follow-up echocardiography showed persistent global cardiac dilatation with slight improvement in right ventricular function.

Baseline hemodynamic parameters from right heart catheterization of both patients are summarized in Table 1.

Table 1
Baseline Hemodynamic Parameters From Right Heart Catheterization

Index Abbreviation	Full Name of Index	Standard Unit	Case 1	Case 2
PAPs	Pulmonary Artery Systolic Pressure	mmHg	44	69
PAPd	Pulmonary Artery Diastolic Pressure	mmHg	35	46
PAWP	Pulmonary Artery Wedge Pressure	mmHg	22	50
CVP	Central Venous Pressure	mmHg	12	23
CO	Cardiac Output	L/min	2.5	2.4
SVRI	Systemic Vascular Resistance Index	dyn·s/cm⁵/m²	4334	5354
PVR	Pulmonary Vascular Resistance	Wood units	6.4	1.7
CVP/PAWP ratio	CVP to PAWP ratio	-	0.55	0.46
PAPi	Pulmonary Artery Pulsatility Index	-	0.75	1.00
RVSWI	Right Ventricular Stroke Work Index	g·m/m²	9.6	14.2

Note: PAPi < 1.85 and reduced RVSWI are independent high-risk factors for right heart failure after LVAD implantation.

3. Surgical Strategy and Perioperative Management Protocol

3.1 Multidisciplinary Decision-Making

Both patients were discussed by a multidisciplinary team including cardiac surgery, anesthesiology, cardiopulmonary bypass, and critical care medicine. Based on comprehensive evaluation including echocardiographic parameters, CMR findings, right heart catheterization-derived hemodynamic indices, and validated risk scoring, it was unanimously agreed that both patients had severe preoperative right ventricular dysfunction, and the risk of postoperative right heart failure after isolated LVAD implantation was extremely high. Therefore, the decision was made to perform concomitant LVAD and temporary RVAD implantation.

3.2 Surgical Procedure

All operations were performed under general anesthesia with moderate hypothermic cardiopulmonary bypass (CPB), established via median sternotomy. The Corheart 6 magnetically levitated LVAD was implanted with the inflow cannula placed at the left ventricular apex, and the outflow tract was established by anastomosing the vascular graft to the ascending aorta. After confirming the optimal position of the device by transesophageal echocardiography (TEE), the rotational speed and flow rate were adjusted.

For the temporary RVAD, an extracorporeal magnetically levitated system (Extra-VAD) was used, with venous drainage established via femoral vein cannulation, and arterial perfusion established by anastomosing the vascular graft to the main pulmonary artery. The rotational speed and flow rate were adjusted after connecting the device. The patient with ischemic cardiomyopathy underwent concomitant coronary artery bypass grafting to achieve complete revascularization.

3.3 Intraoperative Results

For Case 1, the CPB time was 171 min, and intraoperative blood loss was 1300 mL; for Case 2, the CPB time was 164 min, and intraoperative blood loss was 1350 mL. After heparin neutralization with protamine and hemodynamic stabilization, CPB was weaned off, and the chest was closed layer by layer with drainage tubes indwelled.

The final rotational speeds of the LVAD were 2699 rpm and 2548 rpm, with flow rates of 2.73 L/min and 3.29 L/min, respectively; the rotational speeds of the RVAD were 2100 rpm and 2400 rpm, with flow rates of 2.41 L/min and 1.81 L/min, respectively. Both patients were transferred to the cardiac surgical intensive care unit (CSICU) after surgery.

4. Postoperative Outcomes

After surgery, the patients received mechanical ventilation, inotropic agents for circulatory maintenance, precise volume management, dynamic adjustment of device parameters, individualized anticoagulation, anti-infective therapy, and organ function support. Daily bedside echocardiography was performed to monitor biventricular balance, valvular function, and device working status.

The target cardiac index of ≥ 2.4 L/(min·m²) for left ventricular assist support was measured via intermittent thermodilution using a pulmonary artery (Swan-Ganz) catheter, which remains the clinical standard for cardiac output monitoring even with concomitant RVAD support.

During the stepwise weaning of temporary RVAD, the LVAD rotational speed was generally maintained at the initial target level and was not routinely increased synchronously with RVAD down-titration. Daily bedside echocardiography was performed before each RVAD speed reduction to evaluate interventricular septum position, left ventricular filling, and right ventricular contractility. If RVAD down-titration led to excessive left ventricular filling and rightward shift of the interventricular septum, LVAD speed was slightly increased to maintain biventricular balance. The core principle was to maintain a

centered interventricular septum, central venous pressure (CVP) < 14 mmHg, and adequate tissue perfusion.

The perioperative dynamic changes of CVP in both patients are shown in Fig. 1. The dynamic trends of liver and renal function biomarkers and device flow rates are presented in Fig. 2 and Fig. 3, respectively. Intraoperative and postoperative imaging findings are demonstrated in Fig. 4. The clinical course flowcharts of both patients are illustrated in Fig. 5.

4.1 Case 1 Outcomes

The patient was successfully weaned from mechanical ventilation and extubated 24.5 h after surgery, and was switched to bi-nasal oxygen inhalation (5 L/min), with a respiratory rate of 12–23 breaths/min and peripheral oxygen saturation of 99%-100%.

Anticoagulation was initiated on postoperative day 1 with continuous intravenous infusion of unfractionated heparin (UFH). Given the patient's preoperative oral aspirin administration and excessive wound oozing after surgery, activated clotting time (ACT) was maintained at 140–160 s. Warfarin sequential anticoagulation was added on postoperative day 3, with a target international normalized ratio (INR) of 2.5-3.0. Heparin was discontinued after the INR reached the target range on postoperative day 5.

Bedside echocardiography on postoperative day 5 showed significantly reduced cardiac cavity size compared with preoperative values, with LVEDD of 45 mm, right ventricular internal diameter of 24 mm, and improved TAPSE compared with baseline. In the early postoperative period, fluid intake was strictly restricted (approximately 1200 mL/day), and mean arterial pressure (MAP) was maintained above 70 mmHg. The patient developed a transient increase in liver and kidney function indexes after surgery, with acceptable urine output. The indexes gradually decreased after symptomatic and supportive treatment including hepatoprotective, cholagogic, and renoprotective therapy. Thereafter, fluid intake was gradually relaxed, and enteral nutrition support was intensified.

The rotational speed of the RVAD was reduced stepwise under ultrasound guidance on a daily basis after surgery, with dynamic assessment of right ventricular systolic function, cavity size, valve opening, and CVP. After confirming circulatory stability, the temporary RVAD was successfully removed at the bedside on postoperative day 7.

On postoperative day 8, the patient presented with decreased hemoglobin level and melena, with positive fecal occult blood, which was considered gastrointestinal bleeding. Fasting, acid suppression and gastric protection, blood transfusion for anemia correction, and anticoagulation suspension were administered. After the hemoglobin level stabilized and fecal occult blood turned negative, low molecular weight heparin (LMWH) was used for transition, and oral warfarin anticoagulation was gradually resumed.

Early rehabilitation training was initiated on postoperative day 1, including bedside limb movement and ankle pump exercises. On postoperative day 10, the patient was able to sit in a wheelchair and perform bedside assisted activities; he was transferred to the general ward on postoperative day 13; and he was able to walk independently about 100 m with a walker on postoperative day 18. Echocardiography re-examination on postoperative day 16 showed significantly reduced cardiac cavity size, balanced biventricular ratio, regular 1:1 opening of the aortic and pulmonary valves, and no valvular regurgitation. The patient was discharged fully recovered on postoperative day 40.

After discharge, he regularly took warfarin combined with aspirin, as well as standardized anti-heart failure therapy including diuretics, metoprolol, sacubitril/valsartan, and dapagliflozin.

Serial echocardiographic parameters of this patient across different time points are detailed in Table 2.

Table 2
Echocardiographic Parameters of Case 1 at Different Time Points

Index Abbreviation	Full Name of Index	Preoperative Baseline	Preoperative Optimization	Postoperative	1 Month Post-Discharge
AOD	Aortic Root Diameter	33 mm	34 mm	33 mm	34 mm
LAD	Left Atrial Diameter	51 mm	39 mm	35 mm	40 mm
IVSD	Interventricular Septal Thickness at End-Diastole	9 mm	9 mm	10 mm	10 mm
LVDd	Left Ventricular End-Diastolic Diameter	66 mm	60 mm	45 mm	53 mm
LVPWD	Left Ventricular Posterior Wall Thickness at End-Diastole	9 mm	9 mm	10 mm	9 mm
LVDs	Left Ventricular End-Systolic Diameter	60 mm	52 mm	40 mm	45 mm
FS	Left Ventricular Fractional Shortening	9%	13%	16%	16%
SV	Stroke Volume	44 ml	50 ml	51 ml	53 ml
EF(Teich)	Left Ventricular Ejection Fraction (Teichholz Method)	20%	28%	33%	33%
RVD	Right Ventricular Internal Diameter	37 mm	29 mm	24 mm	26 mm
RAD	Right Atrial Dimension	63 mm×46 mm	54 mm×41 mm	46 mm×42 mm	48 mm×46 mm
TAPSE	Tricuspid Annular Plane Systolic Excursion	11 mm	13 mm	16 mm	15 mm
PASP	Estimated Pulmonary Artery Systolic Pressure	53 mmHg	41 mmHg	Normal	Normal

4.2 Case 2 Outcomes

The patient was weaned from mechanical ventilation and extubated 14.75 h after surgery, and was given bi-nasal oxygen inhalation (5 L/min), with a respiratory rate of 12–25 breaths/min and peripheral oxygen saturation of 98%-100%. Bedside echocardiography showed still low myocardial contractility, so dopamine combined with epinephrine was administered to maintain circulation, with a target MAP above 65 mmHg. The vasoactive agents were gradually tapered and discontinued after circulatory stabilization.

UFH anticoagulation was initiated 12 h after surgery, with a target ACT of 160 s, and low-dose warfarin was added for combined anticoagulation on postoperative day 1. Liver enzymes and bilirubin peaked on postoperative day 1, which was considered to be related to underlying right ventricular dysfunction and congestive injury. Liver function basically returned to normal within 1 week after hepatoprotective and cholagogic drug therapy.

The patient had multiple indwelling tubes and long exposure time of invasive devices after surgery, so empirical anti-infective therapy with piperacillin-tazobactam was administered in the early stage. Later, he developed recurrent fever, and the lower respiratory tract pathogen test indicated *Staphylococcus aureus* infection. Vancomycin was added, with monitoring of renal function and blood drug concentration. After poor therapeutic effect, the anti-infective regimen was upgraded to meropenem combined with vancomycin, with well-controlled infection. The pathogen test turned negative after 9 days of medication, and vancomycin was discontinued.

The patient developed delirium in the early postoperative period, and symptoms significantly improved after symptomatic intervention with olanzapine and sertraline. He had intermittent hypernatremia, and oral/nasogastric water supplementation was encouraged to correct electrolyte disturbance and reduce the inducement of delirium.

On postoperative day 3, monitoring via Swan-Ganz catheter indicated relative volume insufficiency, which was considered to be caused by circulatory redistribution after improved cardiac function. Active fluid supplementation was administered, with daily fluid intake controlled at 3000–4000 mL, to optimize preload and stabilize circulation.

The rotational speed of the RVAD was reduced stepwise on a daily basis, and the temporary RVAD was removed and heparin was discontinued on postoperative day 4 after confirming hemodynamic stability. The patient had poor oral intake after surgery, so enteral nutrition combined with oral diet was administered, with albumin supplementation to increase colloid osmotic pressure and reduce tissue exudation, as well as intestinal flora regulation to avoid intestinal flatulence affecting respiratory function.

Echocardiography re-examination on postoperative day 10 showed obvious retraction of the cardiac cavity, with LVEDD of 69 mm, right ventricular internal diameter of 31 mm, and LVEF of 24%. The patient was able to perform bedside assisted activities on postoperative day 11, and was transferred to the general ward on postoperative day 17. Diuresis, nutritional support, and pulmonary rehabilitation training were continued, with dynamic re-examination of chest CT and echocardiography. Bilateral closed

thoracic drainage was performed to remove pleural effusion and promote lung recruitment. The patient was able to walk independently about 100 m with a walker on postoperative day 20. The patient was discharged with improved condition on postoperative day 50.

After discharge, he regularly took warfarin for anticoagulation and standardized anti-heart failure medications.

Serial echocardiographic parameters of this patient across different time points are detailed in Table 3.

Table 3
Echocardiographic Parameters of Case 2 at Different Time Points

Index Abbreviation	Full Name of Index	Admission	Preoperative Optimization	Postoperative	1 Month Post-Discharge
AOD	Aortic Root Diameter	31 mm	34 mm	34 mm	33 mm
LAD	Left Atrial Diameter	50 mm	51 mm	62 mm	61 mm
IVSD	Interventricular Septal Thickness at End-Diastole	8 mm	8 mm	9 mm	9 mm
LVDd	Left Ventricular End-Diastolic Diameter	79 mm	80 mm	69 mm	71 mm
LVPWD	Left Ventricular Posterior Wall Thickness at End-Diastole	8 mm	8 mm	9 mm	9 mm
LVDs	Left Ventricular End-Systolic Diameter	71 mm	71 mm	61 mm	64 mm
FS	Left Ventricular Fractional Shortening	10%	11%	12%	10%
SV	Stroke Volume	71 ml	81 ml	60 ml	55 ml
EF(Teich)	Left Ventricular Ejection Fraction (Teichholz Method)	21%	24%	24%	21%
RVD	Right Ventricular Internal Diameter	41 mm	39 mm	31 mm	30 mm
RAD	Right Atrial Dimension	89 mm×69 mm	87 mm×67 mm	72 mm×56 mm	63 mm×55 mm
TAPSE	Tricuspid Annular Plane Systolic Excursion	11 mm	15 mm	16 mm	15 mm
PASP	Estimated Pulmonary Artery Systolic Pressure	48 mmHg	46 mmHg	Normal	Normal

4.3 Follow-Up Outcomes

At the 2-month postoperative follow-up, both patients had stable hemodynamics, normal device function, no complications such as thrombosis, bleeding, or infection, significantly improved cardiac function, and markedly increased exercise tolerance and quality of life.

5. Discussion

5.1 Preoperative Risk Stratification and Rationale for Concomitant Biventricular Support

Right heart failure is one of the most common and severe complications after LVAD implantation, and is significantly associated with decreased short- and long-term survival, as well as increased incidence of adverse events including gastrointestinal bleeding, stroke, and multiple organ failure [6]. It is reported that approximately 10% of patients undergoing LVAD implantation require temporary or permanent RVAD support during or after surgery [2,7].

The pathophysiological mechanism of post-LVAD right heart failure is as follows: rapid unloading of the left ventricle leads to leftward shift of the interventricular septum, which can cause abnormal contractile geometry of the right ventricle and relative increase in pulmonary vascular resistance. Meanwhile, increased left cardiac output leads to a sudden surge in venous return and a sharp elevation in right ventricular preload, which can rapidly unmask and aggravate pre-existing underlying right ventricular dysfunction, eventually progressing to refractory right heart failure. This pathophysiological effect is more pronounced in patients with severe preoperative right ventricular dysfunction [6].

Therefore, accurate preoperative risk assessment of right heart failure and concomitant implantation of temporary extracorporeal RVAD for short-term biventricular circulatory support in high-risk patients has become the core strategy to prevent refractory right heart failure after LVAD implantation and reduce perioperative mortality [2,4]. This is also the core evidence-based basis for the treatment decision of the two patients in this study.

Accurate preoperative assessment and risk stratification of right ventricular dysfunction are the core prerequisites for determining whether to implant RVAD concomitantly. At present, there are several international risk prediction models for right heart failure after LVAD implantation, such as the Michigan Right Heart Failure Risk Score [8], INTERMACS Right Heart Failure Risk Score [1], and EUROMACS Right Heart Failure Risk Score [9]. Among them, TAPSE < 14 mm, pulmonary artery pulsatility index (PAPi) < 1.85, CVP/pulmonary artery wedge pressure (PAWP) > 0.63, PVR > 2.5 Wood units, and the need for high-dose inotropic support preoperatively have been confirmed as independent high-risk factors for refractory right heart failure after LVAD implantation [8,9].

In this study, both patients had a preoperative TAPSE of 11 mm, complicated with moderate to severe pulmonary hypertension, NYHA functional class Ⅳ, and INTERMACS profile 2–3. CMR confirmed severe right ventricular systolic dysfunction, and right heart catheterization showed reduced PAPi and right

ventricular stroke work index (RVSWI), consistent with multiple high-risk indicators. Preoperative risk stratification using the Michigan score classified both patients as high risk for postoperative right heart failure, supporting the clinical decision of concomitant biventricular support. After optimized medical therapy, there was no significant improvement in right ventricular function, and the risk of postoperative right heart failure after isolated LVAD implantation remained extremely high.

For both early acute right heart failure and early post-implantation right heart failure, temporary RV mechanical circulatory support is designed to stabilize the patient, unload the right ventricle, and provide a time window for the recovery of RV function. Planned temporary RVAD implantation yields better outcomes than delayed implantation, with lower perioperative mortality and fewer end-organ complications [2,7]. Meanwhile, concomitant biventricular assist device implantation, rather than sequential implantation, is associated with a more favorable prognosis, with an annual survival rate of up to 56% [2].

In this study, after multidisciplinary team evaluation, both patients received the strategy of concomitant LVAD combined with temporary RVAD implantation. No refractory right heart failure occurred after surgery, and hemodynamics were rapidly stabilized, which confirmed the rationality and safety of this strategy in high-risk patients. In addition, both patients completed accurate hemodynamic assessment combined with right heart catheterization, and comprehensive risk stratification was performed based on end-organ involvement manifestations such as liver and kidney function injury and diuretic resistance, which provided a comprehensive basis for surgical decision-making.

5.2 Device Advantages and Parameter Matching Strategy for Biventricular Assistance

The Corheart 6 used in this study is a domestic third-generation fully magnetically levitated centrifugal LVAD. Its core technical advantages include small size (weight only 90 g), optimized hydraulic flow channel design, low blood shear stress, as well as excellent anti-reflux performance and rotational speed stability. Compared with imported third-generation magnetically levitated LVAD (such as HeartMate 3), Corheart 6 is more suitable for the BSA and anatomical characteristics of the Chinese population, with lower difficulty of implantation [5,10]. It has been confirmed to have favorable hemocompatibility and short- and long-term safety in domestic multi-center clinical studies, with a significantly lower incidence of device-related complications such as thrombosis and bleeding compared with second-generation axial flow pumps [5,11].

In this study, the BSA of the two patients was 1.61 m^2 and 2.08 m^2, respectively. The small size of Corheart 6 perfectly met the implantation requirements. No pump thrombosis, device failure or other related complications occurred at the 2-month postoperative follow-up, which further verified the clinical application value of this domestic device.

Notably, permanent dual-implantation biventricular assist device (BiVAD) is more suitable for patients with irreversible right ventricular injury and no indication for heart transplantation, but it has the

limitations of high trauma, high risk of infection and thrombosis, and high medical cost [12–15]. In contrast, the combined temporary RVAD regimen used in this study has the advantages of less trauma, bedside stepwise weaning, no need for re-thoracotomy, and providing a transition window for right ventricular function recovery. It is more suitable for patients with preoperatively assessed reversible potential of right ventricular function, and also provides a more cost-effective option for biventricular support in clinical practice.

The core difficulty of biventricular assistance lies in the parameter matching and flow balance of the left and right heart devices [16]. Based on the clinical experience of our center, the adjustment of RVAD rotational speed and flow rate should ensure moderate filling of the right ventricle, and inotropic agents should be combined to maintain right ventricular contractility.

The standardized parameter setting protocol of our center is as follows: the target cardiac index of the left ventricular assist pump is ≥ 2.4 L/(min·m²) (measured by intermittent thermodilution via Swan-Ganz catheter), the RVAD rotational speed is adjusted according to CVP, and the LVAD flow rate is maintained 5%-10% higher than that of RVAD. At the same time, excessively high rotational speed and flow rate of LVAD should be strictly avoided to prevent the increase of aortic pressure leading to aortic insufficiency. After surgery, the pump speed should be adjusted under the guidance of echocardiography to maintain CVP < 14 mmHg while unloading, so as to ensure the centering of the interventricular septum and adequate tissue perfusion. In general, the low rotational speed and low flow rate strategy is preferentially adopted in clinical practice to avoid myocardial disuse atrophy caused by long-term full support, and create conditions for the recovery of right ventricular function [17].

In this study, both patients received a weaning regimen of stepwise reduction of RVAD rotational speed under daily bedside echocardiography and hemodynamic monitoring after surgery, and were successfully weaned from RVAD on postoperative day 7 and day 4, respectively, with a smooth weaning process and no circulatory fluctuation. Combined with the case characteristics, the patient with ischemic cardiomyopathy had myocardial ischemia-reperfusion injury due to concomitant coronary artery bypass grafting during the operation, and the recovery speed of right ventricular function was relatively slow, so the weaning cycle was longer. In contrast, the patient with dilated cardiomyopathy had volume overload as the core preoperative manifestation. After preoperative CRRT and precise postoperative volume management, the right ventricular preload was rapidly optimized, and the right ventricular function recovered faster. This suggests that the timing and regimen of RVAD weaning must be individualized according to the patient's etiology and recovery of right ventricular function.

5.3 Etiology-Based Individualized Perioperative Management

Ischemic cardiomyopathy and dilated cardiomyopathy are the two leading etiologies of end-stage heart failure, with distinct pathophysiological mechanisms of right ventricular dysfunction, which directly determine the difference of perioperative management strategies.

For ischemic cardiomyopathy, right ventricular dysfunction is mainly caused by three mechanisms: right ventricular myocardial ischemia due to right coronary artery stenosis, abnormal interventricular septal movement secondary to left ventricular myocardial infarction, and increased right ventricular afterload due to long-term left heart failure and pulmonary hypertension [18–20]. For such patients, concomitant complete revascularization during surgery is the core prerequisite for improving myocardial perfusion and promoting right ventricular function recovery.

In this study, Case 1 underwent concomitant coronary artery bypass grafting, which achieved complete revascularization of multiple vessels and laid a foundation for postoperative right ventricular function recovery. The core difficulty of perioperative management lies in the balance between bleeding and ischemia: most patients take long-term antiplatelet therapy preoperatively, and surgical trauma and CPB further increase the bleeding risk, while graft patency must be ensured. Therefore, the anticoagulation strategy must be more conservative.

For Case 1, ACT was maintained at 140–160 s in the early postoperative stage, and warfarin sequential anticoagulation was gradually initiated after the bleeding risk decreased, with a target INR of 2.5-3.0 combined with aspirin antiplatelet therapy. This regimen avoided graft occlusion and pump thrombosis without causing severe bleeding events.

For dilated cardiomyopathy, right ventricular dysfunction is mostly related to primary diffuse myocardial involvement, chronic volume overload, and right ventricular remodeling secondary to pulmonary hypertension [22–24]. The right ventricular injury is more diffuse, and the risk of postoperative right heart failure is higher. Case 2 had pre-existing chronic kidney disease, diuretic resistance, severe volume overload, and acute kidney injury requiring CRRT support preoperatively. Therefore, the core of perioperative management lies in precise volume management, maintenance of internal environment homeostasis, and infection prevention and control.

The continuous flow working mode of ventricular assist devices reduces the reliability of traditional volume responsiveness indicators dependent on cardiac pulsation. Our center adopted a multimodal comprehensive volume assessment method integrating pump parameters, bedside echocardiography, passive leg raising test, blood lactic acid level, CVP, daily body weight change, and edema degree. For patients with dilated cardiomyopathy, preload was optimized in the early postoperative stage to correct relative volume insufficiency caused by circulatory redistribution, and negative volume balance was gradually achieved after circulatory stabilization.

Renal function protection is a key component of perioperative management, with different core mechanisms between the two etiologies. For ischemic cardiomyopathy, renal injury is mainly type □ cardiorenal syndrome, driven by insufficient renal perfusion from long-term low cardiac output and impaired renal venous return from venous congestion, compounded by perioperative contrast agent exposure and CPB-related inflammatory response [21]. For dilated cardiomyopathy with underlying chronic kidney disease, renal injury is mostly acute-on-chronic, with additional contributions from long-term RAAS activation, chronic inflammation, and volume overload from diuretic resistance [25–27].

In this study, targeted strategies were adopted for both patients: for Case 1, we focused on maintaining renal perfusion pressure and avoiding excessive diuresis leading to prerenal hypoperfusion; for Case 2, we initiated CRRT preoperatively to correct volume overload, and dynamically adjusted drug dosage according to renal function postoperatively. Both patients had only transient renal function elevation and no persistent renal injury.

In addition, patients with dilated cardiomyopathy mostly have long-term bed rest, malnutrition, and low immunity preoperatively, with multiple indwelling tubes and invasive operations after surgery, resulting in a significantly increased risk of infection and delirium. Case 2 developed *Staphylococcus aureus* pulmonary infection and delirium after surgery, and the infection was effectively controlled and symptoms were relieved by timely upgrading of the anti-infective regimen, symptomatic intervention of psychiatric symptoms, and correction of electrolyte disturbance. This suggests that for such patients, empirical anti-infective therapy, nutritional support, and early intervention of neuropsychiatric symptoms should be strengthened during the perioperative period.

Regardless of the etiology, guideline-directed medical therapy for heart failure should be implemented throughout the whole treatment process. In this study, both patients were gradually started on anti-heart failure drugs such as sacubitril/valsartan, β-blockers, and sodium-glucose cotransporter 2 (SGLT2) inhibitors after hemodynamic stabilization. These drugs can further reverse left ventricular remodeling, improve pulmonary hypertension and right ventricular afterload, and promote the recovery of right ventricular function. Meanwhile, SGLT2 inhibitors can exert renoprotective effects, which are the core choice of drug therapy for heart failure patients complicated with renal insufficiency [28]. Early postoperative rehabilitation training was initiated on postoperative day 1 for both patients, which was closely related to their rapid postoperative recovery and smooth discharge [29].

5.4 Prevention and Control of Key Perioperative Complications

Anticoagulation balance is a persistent clinical challenge in the perioperative management of LVAD combined with RVAD. The low-pressure and low-resistance circulation characteristics of the right heart system and the relatively low flow rate of temporary RVAD will increase the risk of blood stasis and thrombosis [3]. Meanwhile, CPB, surgical trauma, and multi-site vascular puncture significantly increase the risk of bleeding.

In this study, a standardized anticoagulation regimen of UFH bridging warfarin was adopted, with individualized intensity adjustment based on the patient's bleeding risk, etiology, and renal function. No fatal complications such as pump thrombosis or severe intracranial hemorrhage occurred in both patients, which confirmed the safety of this regimen.

It should be emphasized that the anticoagulation intensity of patients with temporary RVAD implantation should be higher than that of patients with isolated LVAD implantation. Meanwhile, ACT, thromboelastography, INR and other indicators should be monitored daily to achieve precise regulation

of anticoagulation. For patients with coronary heart disease, the intensity of anticoagulation and antiplatelet therapy should be balanced, priority should be given to ensuring graft patency, and common complications such as gastrointestinal bleeding should be closely monitored.

Pulmonary hemorrhage is a serious complication that requires high vigilance during temporary RVAD support. Previous studies have shown that temporary RVAD support for more than 7 days and continuous auxiliary flow rate > 4 L/min will significantly increase the risk of pulmonary hemorrhage [30]. Its core mechanism is that non-pulsatile pulmonary perfusion can lead to pulmonary vascular endothelial injury and increased pulmonary capillary permeability, while high-flow perfusion can lead to continuous overload of pulmonary circulation blood volume and aggravate pulmonary vascular injury [31].

In this study, the RVAD auxiliary flow rate of both patients was controlled at about 2.5 L/min, and the weaning time was within 7 days, so no pulmonary hemorrhage complications occurred. This suggests that in the application of temporary RVAD, the auxiliary flow rate and support duration should be strictly controlled. On the premise of ensuring circulatory stability, the lowest effective flow rate should be used as far as possible, and the weaning process should be initiated as early as possible.

Infection is one of the most common complications after LVAD implantation, including driveline infection, pocket infection, bloodstream infection, and pulmonary infection, which is closely related to the short- and long-term mortality of patients [32]. Strict aseptic operation should be performed during the perioperative period, antibacterial drugs should be used rationally, nutritional support and blood glucose management should be strengthened, and various invasive tubes should be removed as early as possible, which are the core measures to reduce the risk of infection.

5.5 Study Limitations and Future Perspectives

This study has certain limitations. First, as a single-center, retrospective case series with only 2 patients included, statistical analysis cannot be performed, and the generalizability of the results is limited. The preliminary findings only provide clinical reference for similar cases and cannot be generalized to a broader population. Second, the follow-up time is only 2 months, which cannot evaluate the long-term prognosis of the patients, the long-term recovery of right ventricular function, the long-term durability of the device and the incidence of long-term complications. Finally, no control group was set up in this study, so it is impossible to compare the long-term prognosis between concomitant temporary RVAD implantation and postoperative rescue RVAD.

Future research can focus on the following aspects: first, carry out multi-center, large-sample cohort studies to further verify the efficacy and safety of domestic magnetically levitated LVAD combined with temporary RVAD in the treatment of end-stage heart failure of different etiologies, and establish a risk prediction model for right heart failure after LVAD implantation suitable for the Chinese population. Second, extend the follow-up time to accumulate long-term follow-up data of domestic Corheart 6 LVAD. Third, explore the optimal weaning timing and standardized weaning process of temporary RVAD, and

optimize the comprehensive scheme of perioperative renal function protection. Fourth, promote the research and development of domestic permanent right ventricular assist devices adapted to the anatomical and physiological characteristics of the right heart, so as to provide more treatment options for patients with end-stage biventricular failure.

Declarations

Ethics Statement

This retrospective case series study was conducted in accordance with the Declaration of Helsinki. The study protocol was approved by the Institutional Review Board of Nanjing First Hospital, Nanjing Medical University. Written informed consent was obtained from both patients for the publication of their clinical data and images.

Conflicts of Interest

The authors declare no conflict of interest.

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Author Contribution

S.N. designed the study, collected and analyzed clinical data, drafted the original manuscript, and revised the manuscript in response to peer review comments.J.W. and L.Y. participated in patient clinical management, collected perioperative clinical data, and performed data collation and verification.H.G. and R.Z. prepared all figures and tables, performed statistical analysis of clinical indicators, and polished the figure legends.C.P. and W.C. participated in the formulation of perioperative management strategies, reviewed the clinical data interpretation, and critically revised the manuscript for important intellectual content.Z.Q. conceived and supervised the study, acquired funding, reviewed and edited the final manuscript, and is the guarantor of the work.All authors have read and approved the final version of the manuscript, and agree to be accountable for all aspects of the work.

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Figures

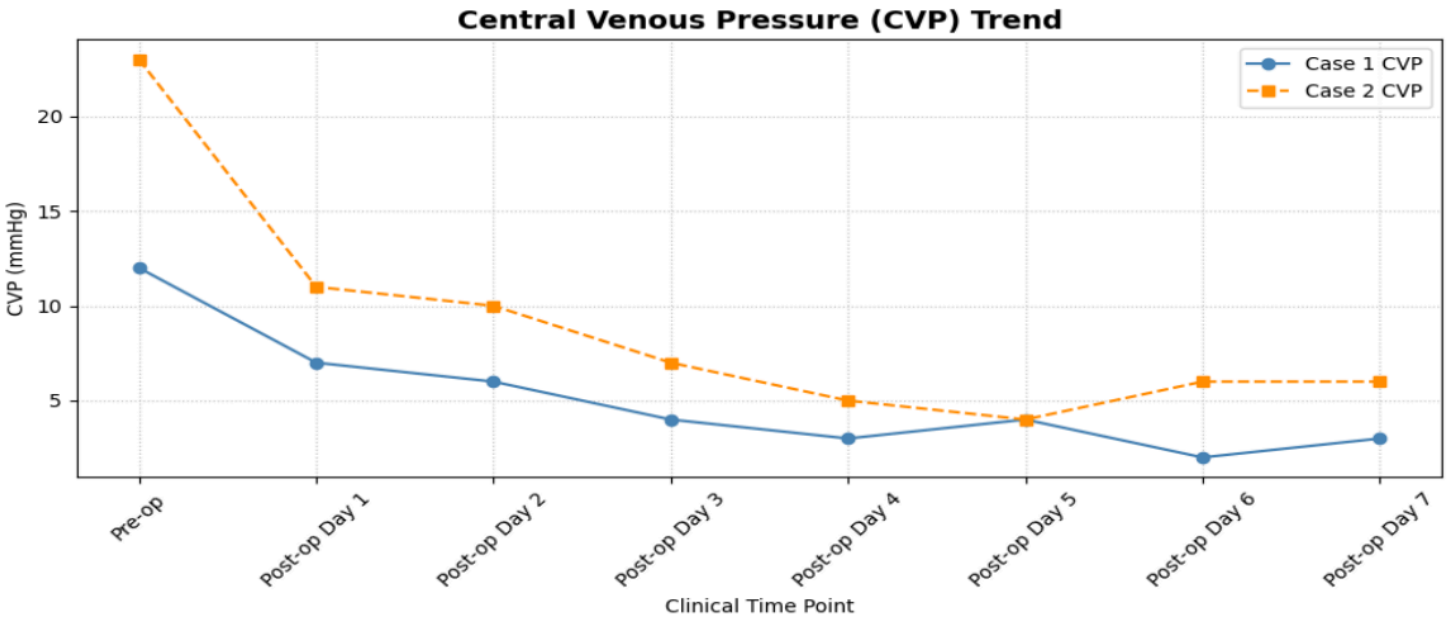


Figure 1

Perioperative Trend of Central Venous Pressure (CVP)

This line graph illustrates the dynamic changes of CVP (unit: mmHg) from the preoperative baseline to postoperative day 7 in the two enrolled patients. The solid blue line with circular markers represents CVP values of Case 1 (ischemic cardiomyopathy), and the dashed orange line with square markers represents CVP values of Case 2 (dilated cardiomyopathy).

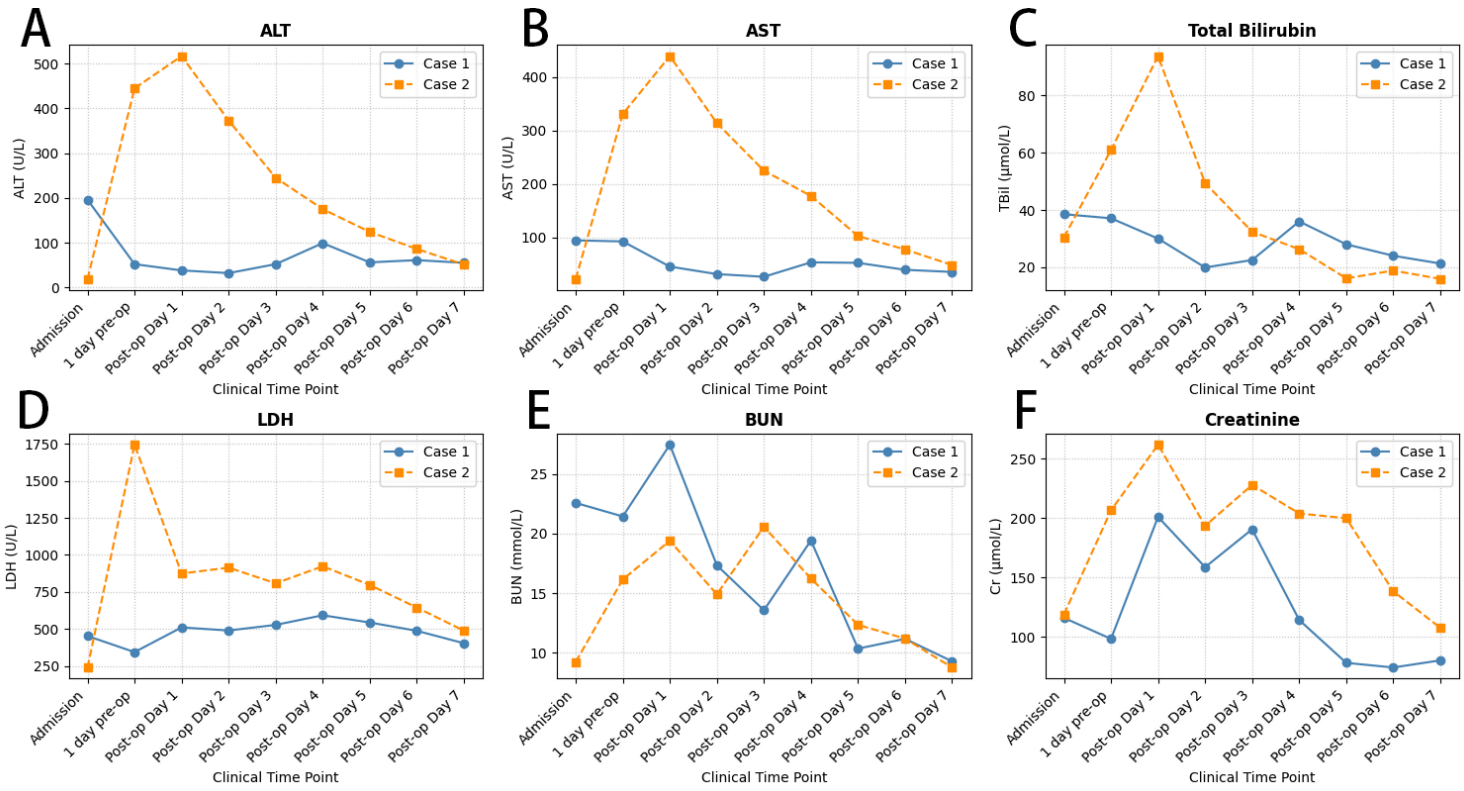


Figure 2

Perioperative Dynamic Changes of Liver Function, Renal Function and Myocardial Injury Biomarkers

This panel graph displays the serial changes of 6 key laboratory biomarkers from admission to postoperative day 7 in the two patients. Panels are as follows: (A) alanine aminotransferase (ALT, unit: U/L), (B) aspartate aminotransferase (AST, unit: U/L), (C) total bilirubin (TBil, unit: μmol/L), (D) lactate dehydrogenase (LDH, unit: U/L), (E) blood urea nitrogen (BUN, unit: mmol/L), and (F) serum creatinine (Cr, unit: μmol/L). The solid blue line with circular markers indicates biomarker levels of Case 1 (ischemic cardiomyopathy), and the dashed orange line with square markers indicates biomarker levels of Case 2 (dilated cardiomyopathy).

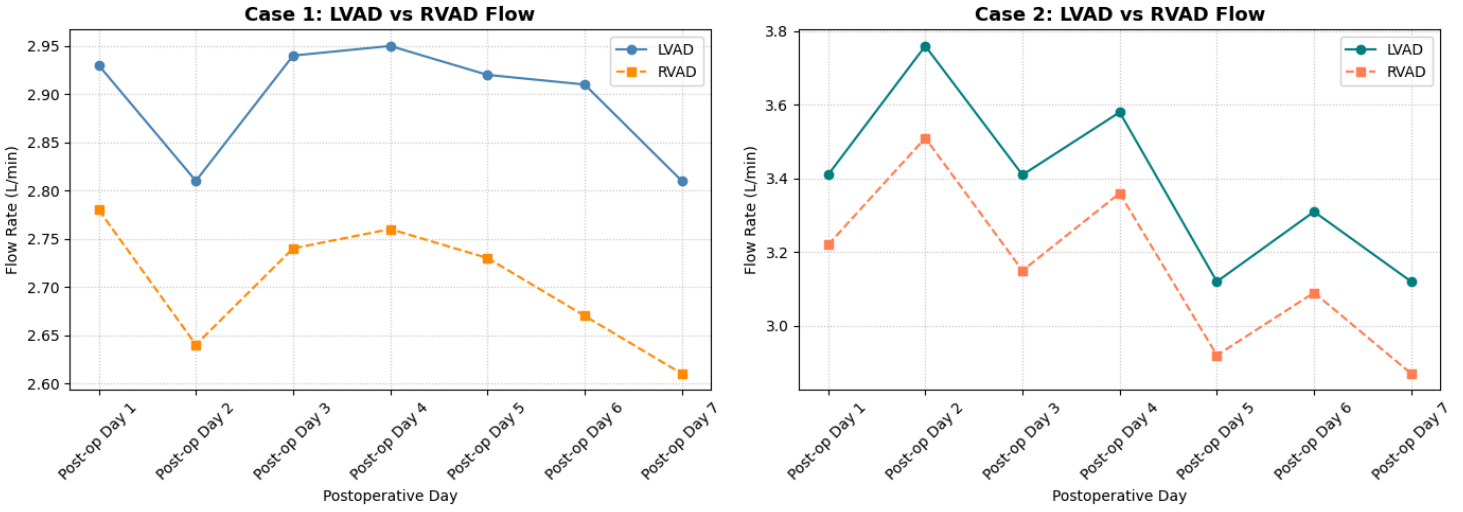


Figure 3

Matched Flow Rate Trends of Left and Right Ventricular Assist Devices Postoperatively

This graph contains two panels showing the daily flow rate (unit: L/min) of the left ventricular assist device (LVAD) and temporary right ventricular assist device (RVAD) from postoperative day 1 to postoperative day 7. The left panel presents the flow trends in Case 1 (ischemic cardiomyopathy): the solid blue line with circular markers indicates LVAD flow, and the dashed orange line with square markers indicates RVAD flow. The right panel presents the flow trends in Case 2 (dilated cardiomyopathy): the solid teal line with circular markers indicates LVAD flow, and the dashed orange line with square markers indicates RVAD flow.



Figure 4

Intraoperative and Postoperative Imaging and Procedures of Ventricular Assist Devices

(A) Intraoperative view after successful implantation of the left ventricular assist device (LVAD) and temporary right ventricular assist device (temporary RVAD). (B) Bedside removal of the temporary RVAD. (C) Postoperative bedside chest radiograph.

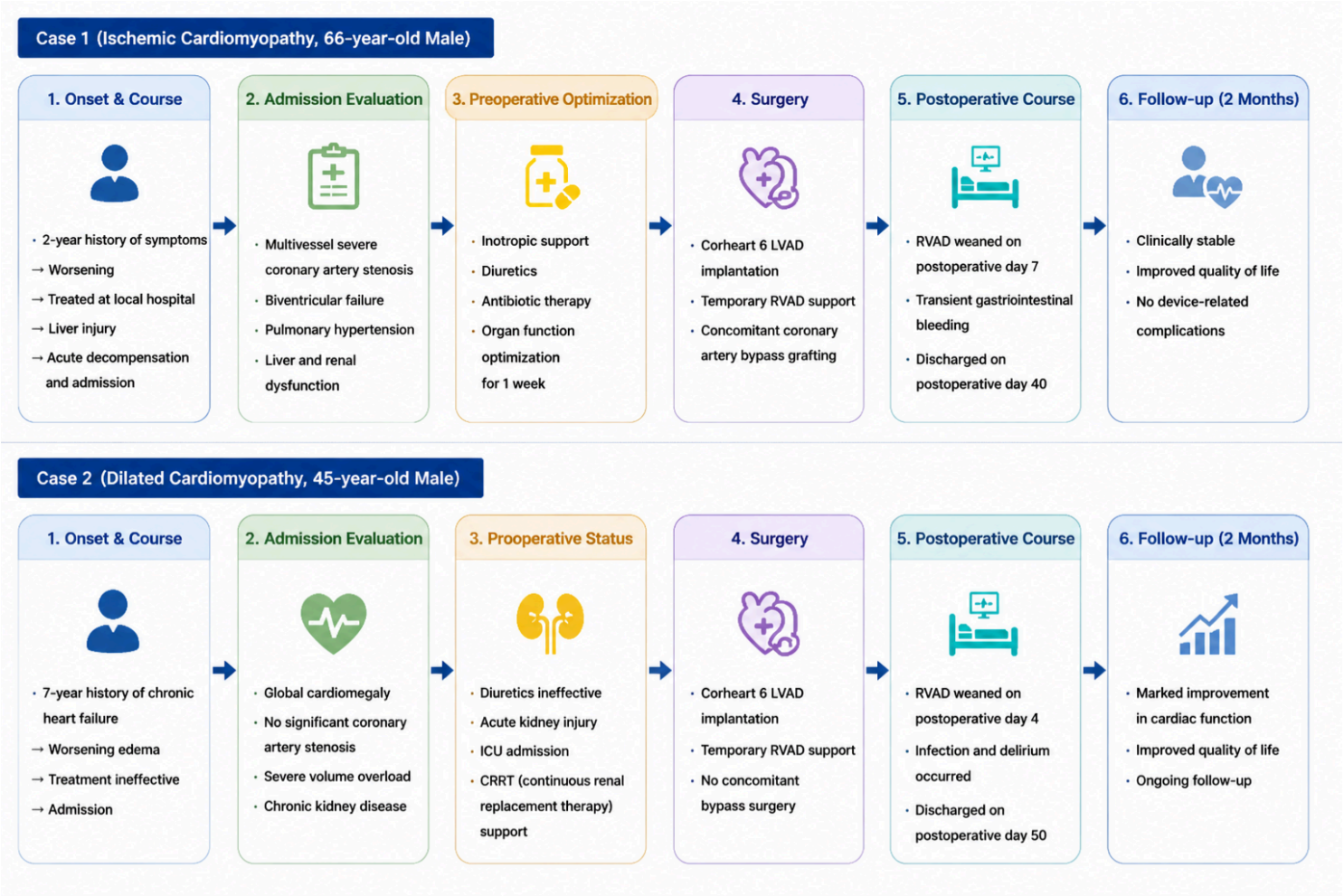


Figure 5

Clinical Course Flowcharts of the Two Patients

This schematic diagram demonstrates the stepwise clinical management process for both patients, from initial presentation to the 2-month follow-up. The upper panel depicts the 66-year-old male patient with ischemic cardiomyopathy, and the lower panel depicts the 45-year-old male patient with dilated cardiomyopathy. Key clinical phases include: (1) Onset and clinical course; (2) Admission evaluation; (3) Preoperative optimization; (4) Surgical intervention (including Corheart 6 LVAD implantation and temporary RVAD support); (5) Postoperative management and complications; (6) Two-month follow-up outcomes. CRRT: continuous renal replacement therapy.