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Right ventricular failure after left ventricular assist devices

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Most patients with advanced systolic dysfunction who are assessed for a left ventricular assist device (LVAD) also have some degree of right ventricular (RV) dysfunction. Hence, RV failure (RVF) remains a common complication of LVAD placement. Severe RVF after LVAD implantation is associated with increased peri-operative mortality and length of stay and can lead to coagulopathy, altered drug metabolism, worsening nutritional status, diuretic resistance, and poor quality of life. However, current medical and surgical treatment options for RVF are limited and often result in significant impairments in quality of life. There has been continuing interest in developing risk models for RVF before LVAD implantation. This report reviews the anatomy and physiology of the RV and how it changes in the setting of LVAD support. We will discuss proposed mechanisms and describe biochemical, echocardiographic, and hemodynamic predictors of RVF in LVAD patients. We will describe management strategies for reducing and managing RVF. Finally, we will discuss the increasingly recognized and difficult to manage entity of chronic RVF after LVAD placement and describe opportunities for future research.

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Left ventricular (LV) assist devices (LVADs) are an increasingly common therapy for advanced heart failure. Most patients with advanced LV dysfunction assessed for an LVAD also have some degree of right ventricular (RV) dysfunction. As a consequence, RV failure (RVF) complicates 10% to 40% of LVAD implants.[1–5] During the past several decades, the unique properties of RV function have been recognized not only in heart failure but also in cardiac surgery, pulmonary hypertension, and now LVAD therapy. The RV differs from the LV in anatomy and physiology, often fails in ways distinct from LV failure, and is critical in determining prognosis even when the LV is successfully treated.

Acute RVF is characterized by the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) as documented elevations of central venous pressure (CVP) and its manifestations, such as edema, ascites, or worsening hepatic or renal dysfunction (Table 1).[6] Severe RVF is described by INTERMACS and most clinical investigators as the need for prolonged post-implant inotropes, inhaled nitric oxide or intravenous vasodilators, or requirement for RV mechanical support. Severe RVF after LVAD implantation is associated with increased peri-operative mortality, prolonged length of stay, and worse survival even after cardiac transplantation.[1,4,5,7] RVF also causes liver, gastrointestinal, and renal congestion, with resulting coagulopathy, altered drug metabolism, malnutrition, diuretic resistance, and poor quality of life.

RV Anatomy and Physiology

The RV is anatomically composed of 3 portions: the inlet (tricuspid valve, chordae tendineae, and papillary muscles), the body, and the outflow tract.[8] The RV myocardium has

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Table 1 Interagency Registry for Mechanically Assisted Circulatory Support Definition of Right Ventricular Failure

RVF definition	Symptoms or findings of persistent RVF characterized by **both** of the following: • Elevated CVP documented by: ◦ Right atrial pressure >16 mm Hg on right heart catheterization ◦ Significantly dilated inferior vena cava with no inspiratory variation on echocardiography ◦ Elevated jugular venous pressure • Manifestations of elevated CVP characterized by: ◦ Peripheral edema (≥2+) ◦ Ascites or hepatomegaly on exam or diagnostic imaging ◦ Laboratory evidence of worsening hepatic (total bilirubin >2.0 mg/dl) or renal dysfunction (creatinine >2.0 mg/dl)
Severity Scale	
Mild	Patient meets **both** criteria for RVF plus: • Post-implant inotropes, inhaled nitric oxide or intravenous vasodilators not continued beyond post-op day 7 after VAD implant **AND** • No inotropes continued beyond post-op Day 7 after VAD implant
Moderate	Patient meets **both** criteria for RVF plus: • Post-implant inotropes, inhaled nitric oxide or intravenous vasodilators continued beyond post-op Day 7 and up to post-op Day 14 after VAD implant Patient meets **both** criteria for RVF plus: • CVP or right atrial pressure >16 mm Hg **AND** • Prolonged post-implant inotropes, inhaled nitric oxide or intravenous vasodilators continued beyond post-op Day 14 after VAD implant
Severe	Patient meets **both** criteria for RVF plus: • CVP or right atrial pressure >16 mmHg **AND** • Need for right ventricular assist device at any time after VAD implant **OR** • Death during VAD implants hospitalization with RVF as primary cause
Severe-Acute	

CVP, central venous pressure; RVF, right ventricular failure; VAD, ventricular assist device.

2 layers. Superficial fibers are arranged circumferentially running parallel to the atrioventricular groove and continue into the LV superficial fibers.[9,10] The deep muscle fibers are aligned longitudinally base to apex. This differs from the LV, where oblique fibers are superficial, with longitudinal fibers in the subendocardium and circumferential fibers in between. These anatomic differences reflect the distinct physiologic functions of the RV.

The RV functions to maintain low systemic venous pressure, provide pulmonary circulation, and adequately fill the LV. In contrast to the high-pressure LV and systemic circulation, the RV and pulmonary circulation are a low-pressure, low-resistance, and highly compliant system. Therefore, the RV is exquisitely sensitive to afterload which is measured clinically as pulmonary vascular resistance (PVR).[11,12] RV performance is also influenced by ventricular interdependence, whereby alterations of one ventricle affect the size, shape, and function of the other due to their close anatomic association.[13] As a result, 20% to 40% of RV output results from LV contraction.[13] Systolic ventricular interdependence is primarily mediated through the interventricular septum (IVS) and diastolic interdependence through the pericardium.[13–15]

Influence of LVAD on RV Function

Interplay between the ventricles changes in the setting of an LVAD. As the LVAD decompresses the LV, and reduces LV end-diastolic pressure, pulmonary artery pressure (PAP) should decrease, resulting in improved RV function. However, multiple mechanisms can combine to cause RVF after LVAD implantation. Increased cardiac output from the LVAD increases venous return to the RV, potentially worsening pre-existing RVF.[16] Excessive leftward shift of the IVS, particularly with overly aggressive LV decompression with continuous-flow (CF) LVADs, may also decrease septal contribution to RV contraction, leading to RVF.[17,18] LV unloading from an LVAD typically reduces tricuspid regurgitation (TR) through decreased RV afterload.[19] However, in the setting of an incompetent valve, increased RV volume and tethering of valve leaflets to a leftward-shifted septum can intensify TR. Volume resuscitation during the peri-operative period may also exacerbate RV dilation and TR.[20]

Tachyarrhythmias also contribute to RVF. Atrial arrhythmias occur in more than 20% of LVAD patients and double the risk of RVF.[21] In addition, ventricular fibrillation may