Device Management and Flow Optimization on Left Ventricular Assist Device Support

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KEYWORDS

- Left ventricular assist device • Heart failure • Mechanical circulatory support
- Pump thrombosis • Device parameters • Ramp study

KEY POINTS

- It is critical to know the device parameters while managing a patient on left ventricular assist device (LVAD) support.
- The LVAD flow depends on interaction between the pump and the native heart and is determined by speed of the pump rotation, preload at the pump inlet, and afterload at the pump outlet.
- The LVAD flow is directly proportional to the device speed (increases at higher speed settings) and inversely proportional to the pressure differential, ΔP, between the inflow and outflow (decreases as ΔP increases).
- Abnormal LVAD flow and pulsatility patterns help recognize LVAD-specific complications.
- Systematic analysis of LVAD parameters and echocardiographic and hemodynamic assessment allow for personalized optimization of LVAD flow.

INTRODUCTION

Left ventricular assist devices (LVAD) improve longevity, functional capacity, and quality of life in patients with refractory, end-stage (stage D) systolic heart failure.[1–3] The original concept of pulsatile flow pumps has been replaced with continuous-flow designs that allowed for miniaturization of the pump sizes, less device-associated infections, and improved device durability.[4] With less mechanical pump failures, long-term LVAD therapy has become a well-accepted reality to support patients until the time of heart transplantation, or as destination therapy for those ineligible for transplantation. As of December 2016, 17,634 patients received US Food and Drug

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Administration–approved continuous-flow LVADs in the Unites States alone with many more implants performed worldwide.[5,6] Currently, 3 continuous-flow LVADs are commercially available for clinical use in the United States: (a) HeartMate-II (Abbott Laboratories, Abbott Park, IL, USA), (b) HVAD (HeartWare Inc, Framingham, MA, USA), and (c) HeartMate-III (Abbott Laboratories, Abbott Park, IL, USA). Most acute care facilities are likely to encounter patients supported with LVADs, and it is imperative that providers of critical care are familiar with the hemodynamic principles of LVAD operation to ensure appropriate care.

In this article, the authors discuss the following:

- Principles of flow optimization in LVAD patients;
- Understanding of normal LVAD physiology and device interaction with the heart;
- Interpretation of LVAD parameters and their application to clinical assessment and patient care.

PRINCIPLES OF LEFT VENTRICULAR ASSIST DEVICE FUNCTION AND NORMAL LEFT VENTRICULAR ASSIST DEVICE PHYSIOLOGY

Contemporary LVADs consist of 3 basic components: an inflow cannula that attaches to the left ventricular (LV) apex or in its proximity and draws blood from the LV chamber into the device, the impeller that moves the volume of blood forward in parallel with native cardiac output, and an outflow tract that returns blood back into the vascular system via the proximal aorta.

The LVAD flow depends on a complex interaction between the pump and the native heart and is determined by the following 3 major components:

1. Programmed speed of the pump rotation,
2. Preload, or pressure/volume of blood available at the pump inlet, and
3. Afterload, or pressure at the pump outlet.

The speed of the device is directly proportional to the pump flow, that is, given a constant preload and afterload, the flow will increase at higher and decrease at lower LVAD speeds. The pressure difference between the pump inlet and outlet, in the absence of obstruction within the inflow cannula or the outflow tract, is termed "head pressure" or "ΔP." The flow of blood through the LVAD is inversely proportional
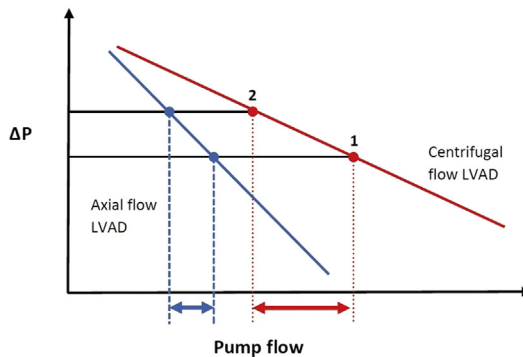
Fig. 1. Schematic representation of HQ curves of axial flow (*solid blue line*) and centrifugal flow (*solid red line*) LVADs, and impact of changing differential pressure ("ΔP") on the pump flow. As "ΔP" increases, the pump flow decreases (move from point 1 to point 2). The same change in "ΔP" will produce greater flow change in the centrifugal pump compared with the axial pump (*solid double-headed arrows*).

to the ΔP, that is, higher flows are generated as pressure differential declines (**Fig. 1**). Thus, the LVAD flow will either increase or decrease when the balance between the systemic blood pressure (afterload) and the LV pressure (preload) changes. That explains why the flow provided by the continuous-flow device is not entirely constant during the cardiac cycle. Preload increases during systole (augmented by native heart contraction), whereas systemic pressure remains relatively constant, which results in a drop of ΔP and an increase in pump flow. On the contrary, during diastole, the pump differential pressure increases and pump flow decreases.

Two conceptually different types of impellers exist to date: axial flow and centrifugal flow designs. In the axial flow pump, the impeller is a cylindrical shaft with 3 spiral blades; the impeller rotates along its axis inside the housing and "pushes" blood forward ("Archimedes screw"). The flow direction of the blood exiting the pump is coaxial to the flow direction entering the pump. The centrifugal flow impeller is shaped like a thick disk with blades that spins around its center of rotation and "propels" the blood outward; the blood enters the centrifuge through the inlet aligned with the rotational axis and leaves the housing perpendicular to the impeller (taking a 90° turn within the housing). Because of differences in design and engineering, the properties of the 2 types of impellers vary from one another. The mechanics and hydrodynamic performance (HQ) of axial versus centrifugal flow pumps are reviewed by Moazami and colleagues.[7] Briefly, the pressure-flow relationship of the LVAD at a given speed is described by the HQ curve, which is unique for each pump. In their recommended operating speed ranges, the axial flow LVADs tend to have steeper HQ curves, whereas the HQ curve of the centrifugal flow LVAD is flatter. The flat curve of centrifugal flow LVAD results in a wide change in flow for a small change in ΔP, whereas the steeper curve of an axial flow LVAD has a smaller variation of flow for the same change in ΔP (see **Fig. 1**). Consequently, an LVAD operating on a flatter segment of the HQ curve is more sensitive to afterload or high blood pressure (elevated systemic vascular resistance [SVR]) and will experience more significant drops in flow in a setting of poorly controlled hypertension. On the other hand, the flatter HQ curve may make the device less prone to over-decompressing the LV and causing suction in response to reduced LV preload (increased ΔP will generate less flow).

POWER, FLOW, AND PULSATILITY

When evaluating a patient, the LVAD parameters should be carefully reviewed in terms of absolute values as well as the trends for the individual patient. The device parameters that

Table 1
Device parameters in commercially available left ventricular assist devices

Device	Flow (L/min)[a]	Speed (rpm)[b]	Power (Watts)	Pulsatility
Heartmate-II	4–8	8800–10,000 (minimum 8600, maximum 12,000)	4–7	4–6
HVAD	4–7	2400–3200	3–7	Waveform pulsatility of 8–2 from peak to trough
Heartmate-III	3–6	5200–5800 (minimum 4800, maximum 6200)	3–7	1–4

[a] Maximal flow on LVAD is up to 10 L/min.
[b] Recommended clinical speed range on the device.

are clinically important are (a) pump speed, (b) power, (c) flow, and (d) pulsatility. The ranges of these parameters in the commercially available LVADs are shown in **Table 1**.

The speed in revolutions per minute is determined and programmed by a health care provider. The power consumption (watts) is a direct measure of the current and voltage applied to the motor. The flow (liters per minute) is calculated from the pump speed and power consumption. It is important to recognize that most of the currently available continuous-flow LVADs do not have flow sensors because of long-term reliability issues. Because the flow is calculated from the power consumption, these 2 parameters move in concert (as power increases, the flow will also increase, and vice versa). Although LVAD flow correlates with the measured cardiac output, the correlation coefficient is low, and the discrepancy between the LVAD flow and measured cardiac output is often seen, because the LVAD flow does not account for the output of the patient's left ventricle into the aorta.[8]

The variability in flow across a cardiac cycle is manifested by the pump pulsatility. It reflects how much cardiac output is provided by the patient's heart versus the pump. The pulsatility is expressed differently for HeartMate-II (axial flow), HeartMate-III, and HVAD (centrifugal flow) devices. For the HeartMate-II and HeartMate-III LVADs, the pulsatility index (PI) is used to quantify flow variation. It is a unitless measure calculated as beat-to-beat amplitude between the maximal flows and minimal flows averaged over 10 to 15 seconds and divided by the average flow according to the formula: (maximum flow – minimum flow)/average flow × 10. A larger difference in the peak instantaneous systolic and diastolic flows will be seen with higher LV contribution to the pump flow or less LVAD support relative to the residual LV contractility and will result in elevated PI. On the other hand, lower LV contractility or higher LVAD speed (more LVAD support) will reduce the numerator in the formula, and PI will be lower. Abrupt change in the PI is referred to as a PI event. Given a stable preload and afterload, changes in speed are inversely related to changes in PI: as the speed is increased, there is less native heart contribution and higher average flow, so the PI decreases. On HVAD, the pulsatility is displayed as a real-time flow waveform (**Fig. 2**A), which allows the operator to see systolic-diastolic variation of flow expressed numerically in liters per minute on the y-axis versus time on the x-axis. The implication of wider versus lower swing in the systolic-diastolic flows is similar to the high versus low PI as discussed above. Review of the flow waveform morphology offers an additional advantage of noting rhythm irregularities (as would be seen in atrial fibrillation) and other characteristic patterns (such as suction events, changes of flow with transitioning from supine to upright position, cough) (**Fig. 2**C).

A suction event is transient obstruction of the inflow cannula by ventricular myocardium typically caused by low preload. The suction alarms in LVADs are triggered by abrupt reductions of flow. In response, the device follows an algorithm to transiently reduce the speed to resolve the event.

Recognition of abnormal patterns on LVAD interrogation is an essential part of patient evaluation at bedside. Systematic analysis of pump parameters in a context of clinical presentation is necessary to diagnose complications and optimize LVAD function (**Fig. 3**).

DECREASED LEFT VENTRICULAR ASSIST DEVICE FLOW

Reduced LVAD flows and powers may be seen with low-speed operation or conditions that decrease LV preload or increase afterload (see **Fig. 3**A). Low LVAD preload states result in over-decompression of the LV and arise from several conditions. Hypovolemia from aggressive diuresis or acute bleeding is a common cause of reduced preload.
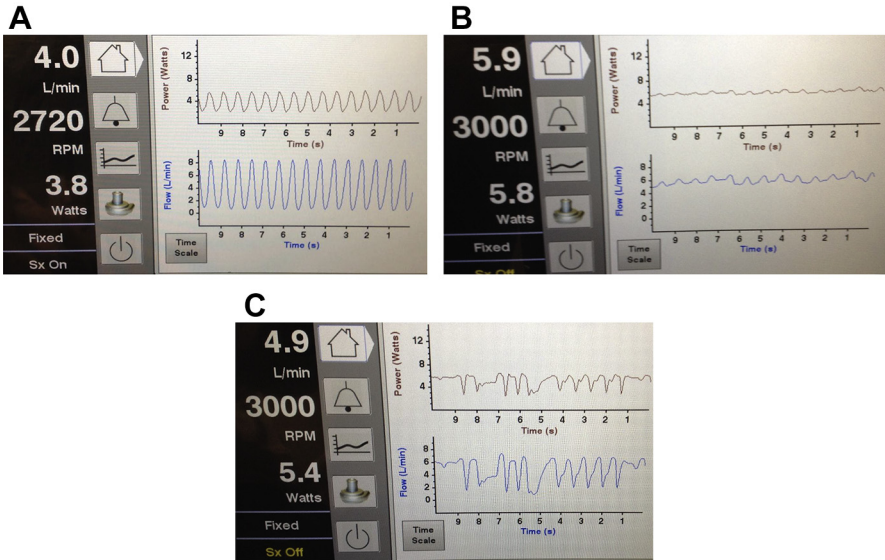
Fig. 2. Examples of high (*A*) and of low (*B*) pulsatility on the system monitor of an HVAD. The high pulsatility was observed in a patient with elevated Doppler-measured blood pressures. The low pulsatility pattern observed in (*B*) is associated with high or normal flows, which may be seen with high-speed operation, vasodilation, or severe AI. When moved from the supine to standing position (reduction in preload), this patient developed suction (*C*). The suction event resolved with reduction of the HVAD speed.

Compromised right ventricular (RV) function and elevated pulmonary vascular resistance also reduce blood return to the LVAD, thus reducing the LV filling pressure and causing a drop in pump flow. The pattern of low flow and low power combined with low PI with frequent PI events (on HeartMate-II and HeartMate-III LVADs), or low-amplitude pulsatility waveform and suction waveforms (on HVAD) may be indistinguishable from hypovolemic states but should raise suspicion for RV failure and trigger clinical investigation. Patients with a failing RV who undergo invasive hemodynamic evaluation will demonstrate elevated central venous pressure (CVP) in a setting of low pulmonary capillary wedge pressure (PCWP), and reduced measured cardiac
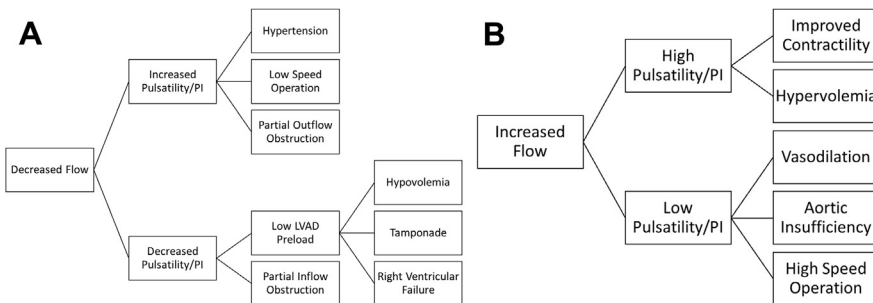

Fig. 3. Flow diagram highlighting typical causes of decreased (*A*) and increased (*B*) LVAD flow.

output. Imaging with bedside echocardiogram may confirm excessive decompression of the LV chamber (small "sucked in" LV) and severely dilated RV, leftward intraventricular septal shift, and severe tricuspid regurgitation (**Fig. 4**). The inflow cannula may come into close contact with the LV myocardium and trigger ventricular arrhythmias, which can further compromise RV function.[9] Atrial arrhythmias may contribute to RV dysfunction and should be corrected expeditiously, especially in the setting of symptomatic RV failure.[10] Inotropic therapies may be required to support RV contractility.[11] In addition, pulmonary vasodilation with inhaled nitric oxide or sildenafil may provide additional benefit by optimizing RV afterload and, therefore, improving RV output.[12,13] In severe cases, implantation of temporary right ventricular assist device may be necessary to ensure adequate systemic perfusion.

Findings of RV failure early after LVAD implantation should also raise the suspicion of pericardial tamponade. Echocardiography may be helpful, but acoustic windows early after surgery are often limited, and computed tomography (CT) of the chest may assist in making the correct diagnosis.[14]

A pattern of low LVAD flow associated with high pulsatility may identify distinct conditions. Hypertension increases afterload and therefore increases ΔP. Initially, hypertension leads to a more pronounced increase in ΔP during diastole. With reduced flow in diastole, the LVAD will display increased pulsatility or PI (see **Fig. 2**A). Severe hypertension can obliterate flow in both systole and diastole. Moreover, mean arterial pressure (MAP) in excess of 90 mm Hg has been shown to increase the risk of pump thrombosis and cerebrovascular events.[15–17] Careful titration of vasoconstrictive infusions to avoid high MAP and initiation of vasodilating medications when appropriate will help optimize pump flow and reduce the risk of complications.

Finally, low LVAD flow with high pulsatility may be simply a product of inappropriately low pump speed setting. Consider increasing the LVAD speed if invasive hemodynamic data suggest left heart failure (high wedge pressure, low cardiac output), and echocardiography demonstrates under-decompression the LV (increased LV chamber size, mitral regurgitation, frequent aortic valve opening).
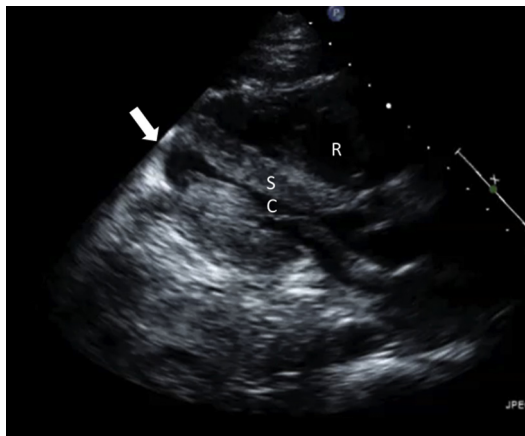
Fig. 4. Echocardiographic findings of a severe case of over-decompression of the left ventricle cavity (C). The inflow cannula (*white arrow*) is visualized in the parasternal long-axis view; the right ventricle (R) is dilated, and the interventricular septum (S) is bowed toward the left ventricle. This constellation of echocardiographic findings may occur in the setting of RV failure, hypovolemia, or high-speed operation.

Obstruction of the inflow cannula may occur as a result of thrombosis, tissue ingrowth, or cannula misalignment. Regardless of the cause, restriction of flow into the inflow cannula will result in diminished preload to the pump and reduced pump flow and power. Depending on whether the nature and degree of obstruction and LV contractility allow for augmentation of flow in systole, the pulsatility may be high, low, or unchanged. On the other hand, obstruction in the outflow tract may be caused by a kink in the graft, thrombosis, or, less commonly, external compression, and increases the afterload for the pump. As discussed above, high afterload will manifest itself as a low-flow and low-power situation on LVAD interrogation, again with variable degree of pulsatility. If suspected, imaging studies may shed light on the cause of abnormal pump findings and hemodynamics. Transthoracic echocardiography may not adequately visualize the inflow cannula because of imaging artifact, and Doppler interrogation of the flow into the cannula may be challenging due to difficulties aligning the ultrasonic beam with the axis of the blood flow. Likewise, distal segment of the outflow conduit and its anastomosis into the ascending aorta may be imaged using transthoracic technique, but more proximal segments of the outflow graft may not be well visualized with this imaging modality.[18] Thus, transesophageal or intravascular ultrasound may be needed to thoroughly evaluate both the inflow cannula and the outflow graft.[19] In addition, CT angiogram with 3-dimensional reconstruction allows for assessment of the course of the outflow conduit (**Fig. 5**).

INCREASED LEFT VENTRICULAR ASSIST DEVICE FLOW

High LVAD flow and power may be related to either increased preload, reduced afterload, or high-speed LVAD operation (see **Fig. 3**B).

The state of hypervolemia (elevated preload) reduces the ΔP leading to higher pump flow at the same pump speed. Clinically, the patient may have pulmonary congestion and peripheral edema despite higher than normal blood flow. Swan-Ganz catheter readings will show elevated CVP and PCWP and normal cardiac output. Echocardiographic evaluation may demonstrate failure to decompress the LV (increased LV
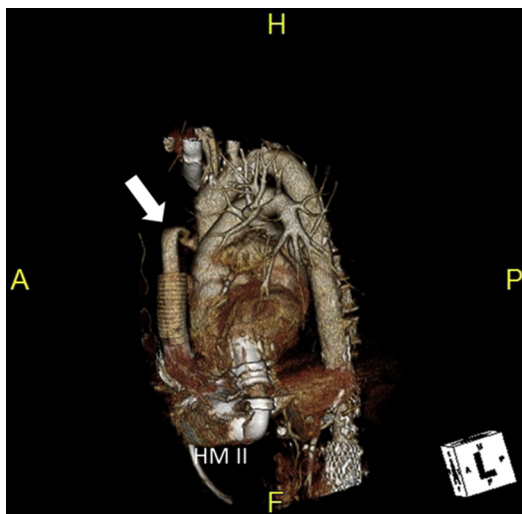

Fig. 5. CT scan with 3-dimensional reconstruction of the LVAD (HM-II) demonstrating obstruction due to a kink (*white arrow*) in the outflow graft. A, anterior (front); F, feet (bottom); H, head (top); P, posterior (back).

chamber size, mitral regurgitation, frequent aortic valve opening) and dilated inferior vena cava. Optimization of volume status with diuretics and/or ultrafiltration will help alleviate the congestion.

A unique condition of high flow and power occurs in the setting of severe aortic insufficiency (AI). As reported by Jorde and colleagues,[20] at least moderate AI develops in 37.6% of patients at 3 years after LVAD implantation. The blood delivered into the aorta by the LVAD recirculates back into the LV instead of reaching systemic circulation. Unlike AI of unsupported heart, which occurs in the diastolic phase of the cardiac cycle only, LVAD-associated AI may be continuous throughout both systole and diastole. As a result, LVAD preload is continuously increased throughout the cardiac cycle, and aortic pressure (afterload) drops rapidly in early diastole, resulting in persistently reduced ΔP, high pump flow, and low pulsatility (similar to waveform shown in **Fig. 2**B). Clinically, the patient with severe AI may present with symptoms of decompensated LV failure despite high LVAD flows. The AI is readily imaged on echocardiography, and right heart catheterization may confirm low measured cardiac output compared with LVAD displayed flow. Managing the LVAD speed with AI can be challenging. Lowering the LVAD speed may reduce the transvalvular gradient and amount of AI or result in increased LV filling pressure provoking exacerbation of heart failure.[21] Conversely, increasing the LVAD speed to "override" the AI may provide temporary relief in some patients. Surgical correction or transcatheter aortic valve implantation or closure is required for definitive treatment.

Vasodilation and low SVR can also lead to a high-flow low-pulsatility state. Causes of reduced SVR may include sepsis, overcorrected hypertension, and, less commonly, profound liver dysfunction, anaphylaxis, or adrenal insufficiency.

Pump thrombosis is a life-threatening complication of LVAD therapy and should be promptly recognized and treated. The hallmark of LVAD thrombosis is increased power with "power spikes" due to increased power consumption required to overcome the drag on the rotor. Because LVAD flow is calculated from the power consumption, the flows on the device interrogation are also "increased," whereas the actual LVAD output is reduced in the presence of large thrombus burden. The presentation may range from asymptomatic biochemical abnormalities (elevated lactate dehydrogenase [LDH] and free plasma hemoglobin concentration), to symptoms of hemolysis (darkening of urine), thromboembolism, stroke, acute decompensated heart failure, or cardiogenic shock. It has been shown that acute increase of LDH concentration is observed as early as 6 weeks before clinically apparent pump thrombosis, making it a sensitive marker for early detection of this devastating complication.[22] In the presence of significant pump malfunction, the echocardiogram will demonstrate inadequate LV decompression, inability to decrease LV diastolic dimension, and failure to "close" the aortic valve during the ramp study (discussed later).[23] Doppler interrogation of the inflow cannula and outflow graft may demonstrate abnormally low flow velocities or absence of blood flow. Intensification of anticoagulation regimen may occasionally resolve signs of hemolysis and normalize pump parameters. There are isolated case reports suggesting benefits of intravascular thrombolytic therapy in carefully selected patients. However, mortality associated with LVAD thrombosis is high and pump replacement is recommended if abnormalities persist despite aggressive anticoagulation. Emergent heart transplantation may also be considered in select cases.[15,22]

Finally, high pump flow with low pulsatility may be seen when the LVAD speed is set too high. In this scenario, the LVAD will compete with the left ventricle for available preload, shifting LVAD contractility down and leftward on the Frank-Starling curve. On echocardiography, the LV may look small (over-decompressed), and the aortic valve

may fail to open. Suction events may occur and may be triggered by provocative maneuvers (orthostatic position change, cough, Valsalva maneuver) (see **Fig. 2**C).

An uncommon finding on LVAD interrogation is high pump flow in a setting of high pulsatility, suggesting some degree of myocardial recovery, which has been reported to occur in less than 1% of patients at 1 year.[24]

RAMP STUDY FOR ASSESSMENT OF DEVICE FUNCTION AND SPEED OPTIMIZATION

Assessment of interaction between LVAD and heart function at changing pump speeds is colloquially described as "ramp studies." These assessments may help diagnose device dysfunction or help identify optimal LVAD speed settings. These assessments can be done with echocardiography (echocardiography ramp study) or hemodynamic measurements (invasive ramp study) alone or in combination.

With increasing impeller speed, normal pump behavior is characterized by progressive decreases in LV dimensions, reduction in severity of mitral regurgitation, reduction in aortic valve leaflet excursion, or opening, and movement of the interventricular septum toward the posterior LV wall. Failure to demonstrate expected echocardiographic changes during the ramp study may identify flow obstruction within the pump (pump thrombosis), especially when combined with elevated LDH concentration (sensitivity of 100% and specificity of 93% with LDH level >5 times the upper limit of normal).[23]

Echocardiogram-guided ramp study is a readily available bedside tool to facilitate optimization of LVAD speed to attain most appropriate LV decompression (evidenced by improved LV diameter and minimized mitral regurgitation) while ensuring favorable RV geometry for more efficient RV function (neutral position of the interventricular septum avoiding leftward septal deviation, which results in increased RV strain and exacerbates tricuspid regurgitation).[25,26] In addition, some operators advocate for LVAD speed to allow intermittent aortic valve opening in order to prevent development of severe aortic regurgitation related to long-term continuous-flow LVAD support.[20]

Uriel and colleagues[27] recently demonstrated the value of invasive hemodynamic ramp study for LVAD speed optimization. It was shown that only 43% of stable LVAD patients managed using clinical and echocardiographic markers had normal right and left cardiac filling pressures, and only 23% had concomitant cardiac index greater than 2.0 L/min/m^2. Thus, right heart catheterization with LVAD speed titration is helpful to assess intravascular volume (guide diuretic therapy), LV decompression (adjustment of LVAD speed), SVR (optimization of afterload), pulmonary vascular resistance (need for pulmonary vasodilation), and RV function (indication for inotrope support in severe cases). In addition, hemodynamic ramp studies may identify abnormal pump behavior. Obstructed LVAD flow is suspected when PCWP fails to decrease and measured cardiac output fails to increase at higher LVAD speed and LVAD-derived flows. Likewise, in the presence of significant AI, ramp study will show minimal LV decompression and cardiac output response at higher LVAD speed.

EVIDENCE-BASED HEART FAILURE THERAPY

Reintroduction of guideline-directed heart failure medical therapy is recommended after LVAD implantation to facilitate myocardial recovery.[11] Furthermore, escalation of medications with vasodilatory properties may augment LVAD flow by reducing ΔP. In some patients, rapid changes in preload and/or afterload may unfavorably affect LVAD function and cause low-flow or suction events.

SUMMARY

Understanding normal physiology of LVADs and recognition of abnormal patterns of flow and pulsatility on device interrogation are essential for successful device and patient management. Despite differences in hemodynamic performance between the axial and centrifugal flow pumps, the basic principles of preload, afterload, and speed management are the same for all contemporary continuous-flow devices. Systematic analysis of LVAD parameters and echocardiographic and hemodynamic guidance allow for optimization and personalization of LVAD flow and detection of LVAD-related complications.

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