CHEST

Mechanical Circulatory Support Devices in the ICU

Keyur B. Shah, MD; Melissa C. Smallfield, MD; Daniel G. Tang, MD; Rajiv Malhotra, MD; Richard H. Cooke, MD; and Vigneshwar Kasirajan, MD, FCCP

The medical community has used implantable mechanical circulatory support devices at increasing rates for patients dying from heart failure and cardiogenic shock. Newer-generation devices offer a more durable and compact option when compared with bulky early-generation devices. This article is a succinct introduction and overview of the hemodynamic principles and complications after device implantation for ICU clinicians. We review the concepts of device physiology, clinical pearls for perioperative management, and common medical complications after device implantation. CHEST 2014; 146(3):848-857

ABBREVIATIONS: AUC = area under the curve; CF = continuous flow; CVP = central venous pressure; ΔP = pressure differential; HQ = hydrodynamic performance; LV = left ventricular; LVAD = left ventricular assist device; MCS = mechanical circulatory support; RV = right ventricular; RVAD = right ventricular assist device; RVF = right ventricular failure; SVR = systemic vascular resistance; TAH = total artificial heart; TTE = transthoracic echocardiography; vWF = von Willebrand factor

The medical community has used implantable mechanical circulatory support (MCS) devices at increasing rates for patients dying from heart failure and cardiogenic shock.[1] Traditionally, these devices were used with the intention to bridge patients to recovery or to heart transplantation. With the development of more reliable continuous flow (CF) left ventricular assist devices (LVADs), there has been a rise in implantation of devices as the definitive therapy for end-stage cardiomyopathy without the intention for heart transplantation (destination therapy). Newer-generation LVADs offer a more compact and durable option when compared with bulky, early-generation devices.[2]

With increasing device usage, physicians have admitted a greater number of patients with MCS to the ICU. From perioperative management to hospital readmissions for complications, the patient with a CF LVAD presents a distinct cardiovascular physiology and unique set of complications. Furthermore, additional devices, including right ventricular assist devices (RVADs) and the total artificial heart (TAH), are used in patients with biventricular dysfunction or anatomic contraindications to an LVAD.

For reference, an early iteration of society-sanctioned guidelines for care of patients with MCS have been previously published, albeit primarily with level C evidence (expert opinion), which highlights the absence of comparative, prospective studies in this field.[3] This article is a succinct introduction and overview of the hemodynamic

Manuscript received November 7, 2013; revision accepted December 26, 2013.

AFFILIATIONS: From the Division of Cardiology (Drs Shah, Smallfield, and Cooke), the Division of Cardiothoracic Surgery (Drs Tang and Kasirajan), and the Division of Pulmonary and Critical Care Medicine (Dr Malhotra), Virginia Commonwealth University, Richmond, VA.

CORRESPONDENCE TO: Keyur B. Shah, MD, Heart Failure/Transplantation, Division of Cardiology, Virginia Commonwealth University, MCV Campus, PO Box 980204, Richmond, VA 23298-0204; e-mail: kshah@mcvh-vcu.edu

DOI: 10.1378/chest.13-2645

principles and complications after MCS implantation for ICU clinicians. For CF LVADs, we review the concepts of device physiology, clinical pearls for perioperative management, and the common medical complications after device implantation. Additionally, we provide a brief overview of the general perioperative and postoperative management of individuals with the TAH.

The general purpose of an LVAD is to use a mechanical pump to draw blood from the left side of the heart and eject it into the aorta. The typical implantable LVAD has an inflow cannula that draws blood from the apex of the left ventricular (LV) cavity and ejects it into the proximal aorta through an outflow cannula (Fig 1). The end result is a parallel circuit to the systemic cardiac outflow that mechanically reduces the LV filling pressure and augments cardiac output. Early-generation assist devices were bulky and cumbersome pumps with poor long-term durability and a high frequency of mechanical failure. These displacement pumps have been replaced with CF technologies, which allow for a smaller and more durable design. CF pumps consist of a rapidly rotating, electromagnetically driven impeller that pumps blood in either an axial (linear; ie, HeartMate II; Thoratec Corporation) or centrifugal (tangential; ie, HVAD; HeartWare Inc) direction (Fig 2).

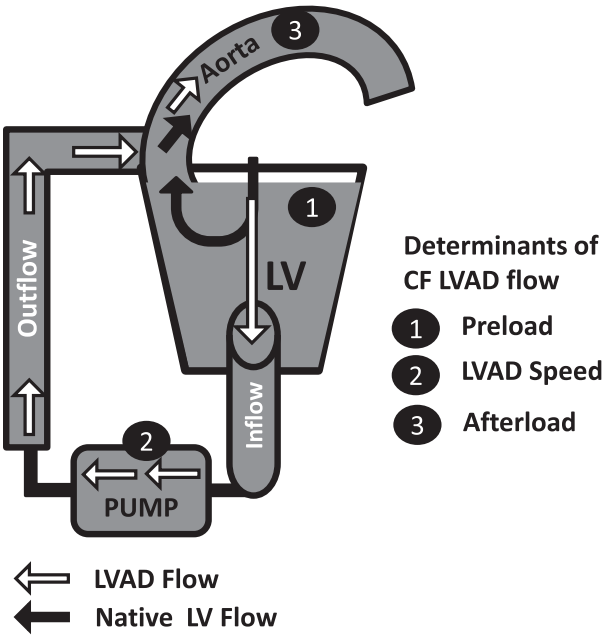

Figure 1 – *The diagram depicts the general configuration and determinants of blood flow for a CF LVAD. The LVAD flow is parallel to the native circulation and is determined by the preload, afterload, and LVAD speed. CF = continuous flow; LV = left ventricle/ventricular; LVAD = left ventricular assist device.*

Flow through a CF LVAD is dependent on the rotational speed of the impeller (set by the user) and the pressure differential (ΔP) from the inlet cannula (preload) to the outlet cannula (afterload). As the ΔP increases, the flow or work performed at a given speed decreases. In other words, pump flow increases by decreasing systemic vascular resistance (SVR) and optimizing blood volume availability in the LV cavity. Since the ΔP changes through the cardiac cycle, flow through a CF LVAD is not completely continuous but also changes throughout the cardiac cycle (Fig 3) with augmentation of flow during systole.

Each LVAD has its own unique hydrodynamic performance (HQ) curve, which describes the relationship of ΔP and flow at various pump speeds. Generally speaking, the HQ curve for centrifugal flow LVADs tends to be more flat, where a small change in the ΔP results in a wide change in flow. Conversely, the HQ curve for axial flow devices tends to be steeper, where a change in the ΔP results in a small change in flow. Because of these operating characteristics, centrifugal-flow LVADs tend to be more sensitive to high SVR states than axial-flow LVADs. Centrifugal flow pumps may exhibit low pump output and inadequate LV unloading when afterload (ie, BP) is increased. Alternatively, centrifugal-flow LVADs are less likely to over-decompress the left ventricle if there is an abrupt drop in preload. If the ventricle becomes too decompressed, the myocardium may crowd the inflow cannula, leading to obstruction of blood flow, colloquially described as a "suction event." A suction event may cause symptoms from disruption of flow or may be a subclinical event and detected only by algorithms programmed in the controller of the LVAD. A comprehensive review has been published by Moazami et al[4] comparing the mechanics and physiology of these two device platforms.

Perioperative Management

In the postoperative period, one may frequently observe unstable hemodynamics and fluctuations in LVAD flow, which may be due to a number of causes (Tables 1, 2). A systematic approach is necessary to diagnose these problems and implement appropriate treatment. Many of these patients are critically ill prior to LVAD implantation with existing or impending end-organ dysfunction. Patients may have pulmonary edema from cardiogenic shock, profound disturbances in coagulation, and unrecognized sepsis from central IV catheters or temporary mechanical support. Early postoperative problems that may lead to hemodynamic instability (discussed in more detail later) include right ventricular (RV) failure,

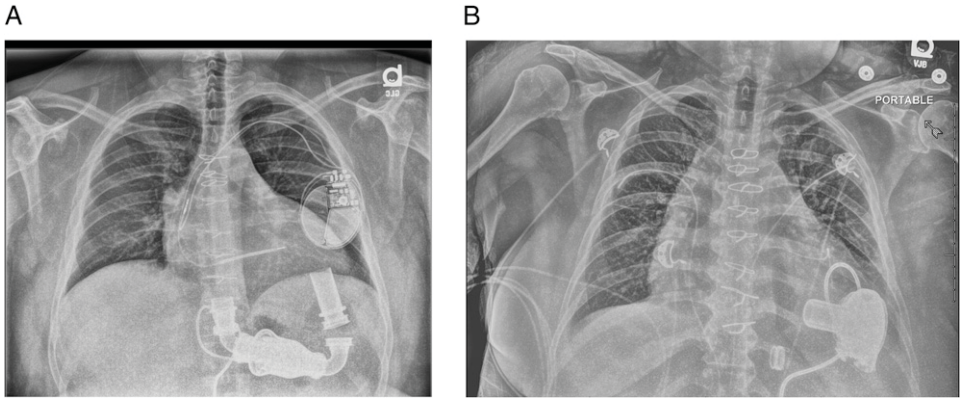

Figure 2 – *A, Chest radiograph of an axial-flow LVAD. B, Chest radiograph of a centrifugal-flow LVAD. See Figure 1 legend for expansion of abbreviation.*

bleeding, infection, LVAD dysfunction, and multiorgan failure. Use of transthoracic echocardiography (TTE) in the immediate postoperative period is often limited because of poor acoustic windows Transesophageal echocardiography, routinely used intraoperatively, can overcome the technical limitations of TTE for postoperative LVAD troubleshooting. Additionally, invasive hemodynamic monitoring with a pulmonary artery catheter and arterial line are often invaluable and can guide management of inotropes, vasopressors, LVAD speed setting, and volume resuscitation/removal.

Left-Sided Heart Failure in Patients With LVAD

Left-sided heart failure after LVAD implantation can have a variety of causes and may be related to suboptimal pump parameters or pump-related complications. Patients with evidence of clinical heart failure on imaging (failure to decompress left ventricle, mitral regurgitation, opening of the aortic valve) or hemodynamic evaluation (elevated pulmonary capillary wedge pressure) may simply need adjustments to increase LVAD flow. Increasing the LVAD speed or reducing the SVR (vasodilation, withdrawal of vasoconstrictors) will augment LVAD flow and, thus, increase cardiac output and decompress the LV. Persistent or severe left-sided heart failure warrants expeditious and comprehensive evaluation of LVAD function. Several potential pathologies must be considered, including pump thrombosis, cannula obstruction/migration, and aortic valve regurgitation.

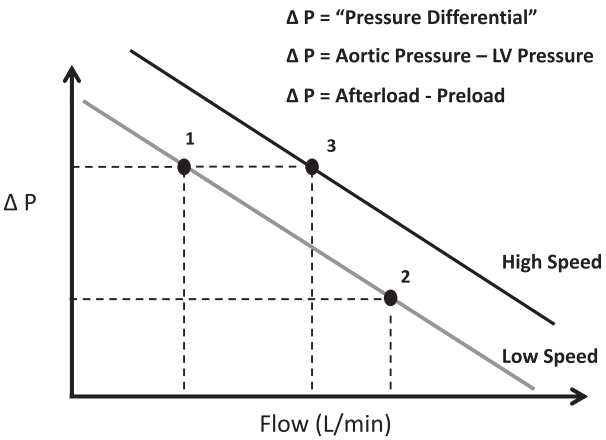

Figure 3 – *A generic hydrodynamic performance curve for a CF LVAD, where the ΔP is on the y-axis and LVAD flow is on the x-axis. Curves are generated for various LVAD speeds. At a given speed, an increase in the ΔP results in a decrease in flow (move from number 1 to number 2) and vice versa. At a given ΔP, an increase in LVAD speed results in increased LVAD flow (move from number 1 to number 3). ΔP = pressure differential. See Figure 1 legend for expansion of other abbreviations.*

The clinical presentation of pump thrombosis after LVAD implantation can range from subclinical laboratory abnormalities to overt heart failure with high-grade clinical manifestations of hemolysis. Severe cases can result in cardiogenic shock and even pump stoppage. The initial presentation may be a cerebrovascular accident, especially if the clot extends beyond the pump housing. Predisposing factors may include interruptions in anticoagulation, infection, and low flow conditions (ie, high SVR).

Clinical evidence of hemolysis, power spikes, and inadequate decompression of the LV on echocardiography (TTE or transesophageal echocardiography) should raise the suspicion for thrombosis. Clot around the impeller may cause intermittent or persistent increases in the power requirements from increased drag on the rotating element in the pump (Fig 4). Severe cases can result in narrowing of the blood flow pathway and disruption of laminar flow leading to RBC destruction. Laboratory analysis often reveals anemia, hemoglobinuria, and a sharp rise in lactate dehydrogenase, plasma-free hemoglobin, and indirect bilirubin.[5]

TABLE 1] Early Postoperative LVAD Complications

Cause	Clinical Findings	Therapeutic Considerations
RV failure	End-organ dysfunction	Inotropes
	↑CVP	Pulmonary vasodilators
	Dilated right ventricle and decompressed left ventricle	Inhaled NO/prostacyclin
	Pump parameters: ↓flow, ↓power, ↓ pulsatility	PDE5 inhibitors
	Suction events	Avoid blood products
		Correct arrhythmias
		RVAD
Tamponade	Hypotension	Surgical reexploration
	↑CVP	
	Pericardial effusion	
	Pump parameters: ↓flow, ↓power	
	Suction events	
Hypovolemia	↑Chest tube output	Volume resuscitation
	Pump parameters: ↓pulsatility	↓Speed

CVP = central venous pressure; LVAD = left ventricular assist device; NO = nitric oxide; PDE5 = phosphodiesterase type 5; RV = right ventricular; RVAD = right ventricular assist device.

Echocardiography usually reveals evidence of inadequate LV decompression: dilated LV cavity, mitral regurgitation, and frequent opening of the aortic valve. Turbulent flow near the inflow cannula or increased inflow velocity may be associated with obstruction or thrombosis.[6] A bedside TTE with a ramping protocol can evaluate the interaction of the LVAD with the LV and detect pump thrombosis, possibly even before a

TABLE 2] Postoperative LVAD Complications

Clinical Presentation	Clinical Findings	Therapeutic Considerations
Pump thrombosis	Left-sided heart failure	Intensify anticoagulation and antiplatelet therapy
	Left ventricle dilated, AV opening frequently, ↑MR	Systemic or directed thrombolytic therapy
	Pump parameters: ↑power or spikes in power (drag on rotor)	Pump exchange
	Evidence of hemolysis	Emergent transplant
	Rising LDH	
	Anemia, renal failure	
	Dark urine	
Inflow cannula obstruction (due to cannula migration or LV remodeling)	May present with heart failure	Volume resuscitation
	Pump parameters: ↓power	Decrease speed
	High inflow velocity with turbulent flow	Surgical repositioning
	CT imaging can confirm	
Outflow kink/obstruction	Pump parameters: ↓power, CT imaging can confirm	Reexploration of chest if symptomatic
Aortic regurgitation	Heart failure with severe cases	AV surgery
	Left ventricle dilated	
	Pump parameters: ↑power, ↑flow (recirculation)	

AV = aortic valve; LDH = lactate dehydrogenase; LV = left ventricular; MR = mitral regurgitation. See Table 1 legend for expansion of other abbreviation.

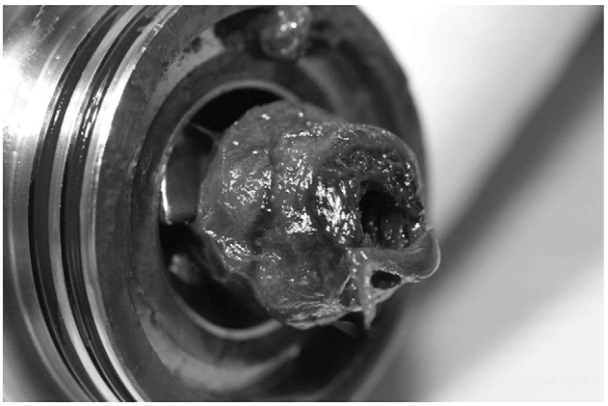

Figure 4 – *Photograph of thrombosis of an LVAD impeller that resulted in LVAD failure and prompted a pump exchange. See Figure 1 legend for expansion of abbreviation.*

fulminant decompensation occurs. For example, a protocol developed at Columbia University assesses the response of LV end-diastolic dimension, frequency of aortic valve opening, valvular insufficiency, and HeartMate II LVAD parameters with incremental changes in the LVAD speed.[7] "Unresponsive" parameters to speed changes may indicate the presence of pump thrombosis and, thus, inadequate LVAD function.

Intensification of anticoagulation or in some cases administration of thrombolytic therapy have been successfully used to treat the early stages of pump thrombosis, especially if the clinical presentation suggests acute clot formation.[8] More significant thrombosis requires consideration of pump exchange or, if appropriate, emergent transplantation.[9,10]

Cannula obstruction is a potential source of LV failure after LVAD implantation. The inflow cannula may be obstructed from tissue ingrowth, thrombosis, or misalignment of the cannula orifice into the myocardial wall.[11] The ideal inflow cannula position after device implantation is directed toward the mitral valve. The position of the inflow cannula may "migrate" from the time of surgery because of change in body habitus or changes in ventricular geometry from chronic unloading and positive ventricular remodeling. Echocardiographic assessment may reveal abnormal Doppler assessment and color-flow mapping of blood flow into the LVAD, whereas CT scanning may confirm the diagnosis.[12] A reduction in the device speed may abrogate the effects; however, in extreme cases, reoperation for adjustment of cannula position and/or device replacement may be necessary.

Kinking of the outflow cannula can also lead to suboptimal LVAD function. Echocardiography may be used to evaluate the distal portion of the outflow cannula as it inserts into the ascending aorta. CT scanning is often required to more comprehensively evaluate the outflow cannula itself.[13]

Aortic valve insufficiency is also a potential source of left-sided heart failure after LVAD implantation, as blood ejected from the LVAD recirculates into the LV cavity rather than reaching the systemic circulation. With normal LVAD function, the retrograde flow into the aorta can lead to fusion of the valve leaflets and degeneration over time.[14] Risk factors for aortic insufficiency include preexisting aortic valve disease and persistent closure of the aortic valve. A thorough investigation of the aortic valve prior to LVAD implantation is warranted. Aortic valve insufficiency may be progressive and may occur remotely from the implantation. Patients who develop significant aortic insufficiency will often have significant increases in pump flow parameters. An increase in pump flow should initiate an evaluation of the competency of the aortic valve. Surgical correction of severe aortic insufficiency after LVAD implantation has been reported using a variety of techniques, including aortic valve over-sewing, leaflet repair, or bioprosthetic valve replacement.[15]

Right-Sided Heart Failure in Patients With LVAD

Competent RV function promotes an adequate reservoir of blood (preload) for the LVAD to eject into the systemic circulation. RV dysfunction can impair optimal LVAD function, and RV failure (RVF) remains a cause of morbidity and death after LVAD placement. RVF is associated with a higher incidence of reoperation for bleeding, higher transfusion requirements, increased inotrope use, and/or RVAD placement and decreased survival.[16]

We do not completely understand the mechanism of RVF after LVAD; however, several factors likely contribute to worsening RV dysfunction of the intrinsically myopathic heart. LV decompression from the LVAD may decrease the septal component of RV contraction, thereby decreasing RV stroke work. Furthermore, septal shift has been associated with worsening tricuspid regurgitation due to annular dilation. Some have hypothesized that the myopathic RV is incapable of handling the increased cardiac output and venous return after insertion of an LVAD.[17] Inflammation associated with transfusion of blood products may induce pulmonary vasoconstriction and further impair forward flow.[18]

Several investigators have formulated risk prediction models using variables associated with hemodynamic evidence of RV dysfunction, end-organ dysfunction, and

severity of illness to predict which patients may develop RV dysfunction after LVAD implantation. Kormos et al[16] defined RVF in the HeartMate II trial as need for RVAD support, inotropic support for at least 14 days, or inotropic support starting > 14 days after implant. The investigators found preoperative ventilator use (OR, 5.5; 95% CI, 2.3-13.2; $P < .001$), a central venous pressure (CVP) to pulmonary capillary wedge pressure ratio of > 0.63 (OR, 2.3; 95% CI, 1.2-4.3; $P = .009$), and blood urea nitrogen concentration > 39 mg/dL (OR, 2.1; 95% CI, 1.1-4.1; $P = .02$) were independent predictors of RVF. Fitzpatrick et al[19] developed an algorithm for predicting RVF with high accuracy that includes cardiac index < 2.2 L/min/m^2 (OR, 5.7; 95% CI, 1.3-24.4; $P = .02$), RV stroke work index ≤ 0.25 mm Hg × L/m^2 (OR, 5.1; 95% CI, 2.1-12.2; $P = .0002$), serum creatinine concentration ≥ 1.9 mg/dL (OR, 4.8; 95% CI, 1.9-12.0; $P = .001$), history of cardiac surgery (OR, 4.5; 95% CI, 1.7-11.8; $P = .002$), severe preoperative RVF (OR, 5.0; 95% CI, 2.0-12.5; $P = .0006$), and systolic BP < 96 mm Hg (OR, 2.9; 95% CI, 1.2-6.9; $P = .02$). Matthews et al[20] developed a point system for predicting RVF that includes preoperative vasopressor use and laboratory markers of renal and hepatic function (area under the curve [AUC], 0.73; $P < .05$).[20] A more recent study by Atluri et al[21] looked at CVP > 15 mm Hg, severe RV dysfunction, preoperative intubation, severe tricuspid regurgitation, and heart rate > 100 as criteria for predicting RVF. These variables were used to create a five-point risk score and showed improved predictive value compared with the Matthews risk score (AUC, 0.80 vs 0.61; $P < .008$).[21]

Echocardiography may further improve the discriminatory power of clinical risk prediction models. In a separate cohort, Grant et al[22] found that reduced RV longitudinal strain (< −9.6%) on TTE incrementally improved the ability of the Matthews score to predict RVF (AUC, 0.77 vs 0.66; $P < .01$). In another study, an increased RV to LV diameter ratio (> 0.75) on TTE was independently predictive of postoperative RVF (AUC, 0.68; $P = .005$) and improved the predictive ability of both the Matthews and Kormos models.[3]

Persistent end-organ dysfunction, venous congestion, and low cardiac output despite decompression of the left ventricle occur with RVF early after device implantation. On echocardiography, this is often associated with the presence of a decompressed left ventricle and a dilated, hypocontractile right ventricle. The LVAD monitor will, typically, show decreased power and flow due to decreased LV preload. The patient may experience frequent suction events and arrhythmias from LV over-decompression and cannula irritation of the myocardium.

Acute RVF from intraoperative stress on an already myopathic right ventricle often improves with time, volume optimization, and supportive measures such as decreasing RV afterload and improving RV contractility. RV contractility can be increased with inotropes or IV catecholamines (preferably at doses that minimize vasoconstrictive effects).[3] Inhaled nitric oxide or inhaled prostacyclin can decrease pulmonary artery pressure and pulmonary vascular resistance, thereby improving RV contractility by decreasing RV afterload.[23] Sildenafil has been shown to facilitate weaning of inhaled nitric oxide without significant effect on systemic blood pressure.[24] Severe tricuspid regurgitation may be corrected during LVAD insertion; however, the benefit for preventing RV failure is poorly defined.[25] Additionally, avoiding blood transfusions (and the associated rise in pulmonary vascular resistance) by perioperatively correcting coagulopathies and achieving meticulous hemostasis is associated with improved outcomes.[26] Persistent or worsening RV failure despite medical therapy may prompt implantation of an RVAD.

Arrhythmias

Ventricular and atrial arrhythmias frequently occur after LVAD implantation and can impair optimal LVAD function. The cause of ventricular arrhythmias may be related to preexisting myopathic substrate, the newly cored apical cannula insertion site, or irritation of the endocardium by the inflow cannula (ie, during suction event). Patients with ventricular arrhythmias prior to LVAD implantation are more likely to have ventricular arrhythmias after device implantation.[8]

Arrhythmias can compromise RV function, consequently reducing LV preload and flow through the LVAD. Symptoms may be subtle or result in overt heart failure. During rapid arrhythmias, the patient experiences suction events, and the LVAD may display low flow and power on the monitor. An echocardiogram can help diagnose arrhythmias related to cannula irritation and over-decompression, and the clinician may then consider reducing the LVAD speed, evaluating/treating hypovolemia, or screening for RVF. For symptomatic patients, treatment with oral antiarrhythmic agents, direct current cardioversion, and ablation is appropriate. The clinical benefit of implantable defibrillators in this population has not yet been defined.

Infections

Standardized definitions of LVAD-related infections are divided into three categories: LVAD-specific infections (ie, pump, cannula, driveline), LVAD-related infections (ie, endocarditis, bloodstream infections, mediastinitis), and non-LVAD infections (ie, pneumonia, urinary tract infection).[27]

Although the frequency of driveline infections has decreased, likely because of decreased driveline diameter, smaller pump pockets, and improved implanting techniques, they continue to be the most common infection in patients with LVAD, occurring in 17% to 30% of patients. Risk factors for driveline infection include young age, obesity, and a history of diabetes mellitus.[28] The causative microorganisms are, typically, skin flora (staphylococcal and enterococcal species), whereas gram-negative bacterial and fungal infections are seen less frequently.[29] Although data determining efficacy of antimicrobial treatment regimens are lacking, superficial infections, if caught early, can be managed with antibiotics and wound care. However, deeper infections may require surgical debridement. Additionally, external driveline stabilization (ie, abdominal binder) to prevent repeated trauma to the exit site may reduce the risk of driveline infection.[30] Infections originating in or migrating to the pump pocket are serious, albeit infrequent, complications that may require protracted courses of IV antibiotic therapy, urgent LVAD replacement, or heart transplantation.

GI Bleeding

GI bleeding is a frequent complication after implantation of a CF LVAD, and various studies have demonstrated the incidence of GI bleeding to be between 5% and 30%.[31] Aggarwal et al[32] demonstrated that the majority of bleeding events were of "upper" rather than "lower" GI origin (57% vs 35%), with erosions, arteriovenous malformations, and gastric ulcers accounting for the majority of events. GI bleeding is a frequent cause for rehospitalization, requiring transfusion of blood products (increasing risk of sensitization) and reduction of antiplatelet and anticoagulant therapy (increasing the risk of thrombotic complications).

The high frequency of bleeding is likely multifactorial in origin. Similar to patients with severe aortic stenosis (Heyde syndrome), patients with CF LVADs develop an acquired von Willebrand factor (vWF) deficiency.[33] Although total vWF levels are maintained, patients with CF LVAD have a pronounced reduction in multimeric vWF proteins, which participate in platelet activation and hemostasis. This reduction occurs early after device implantation, with correction after device removal.[34,35] It has been proposed that the decreased pulse pressure associated with CF LVAD therapy may promote angiodysplasia by modulating angiogenic growth factors.[31] Further supporting this theory, a lower incidence of nonsurgical bleeding has been observed in patients who have device-measured parameters of increased pulsatility.[36]

No proven therapies for the treatment of LVAD-associated GI bleeding exist. In addition to standard measures to identify the source of bleeding and resuscitate the patient, some have considered increasing pulsatility by reducing LVAD speed or instituting inotropes. Additionally, patients often require reduction or removal of warfarin and antiplatelet therapy.

Octreotide (somatostatin analog) may be effective to treat and prevent GI bleeding in patients with LVAD.[37] Octreotide works to reduce variceal bleeding and idiopathic GI bleeding by inducing splanchnic vasoconstriction, enhancing platelet aggregation, and inhibiting angiogenesis.[38] Additionally there are data supporting the use of octreotide for vWF syndrome and arteriovenous malformations, two conditions proposed to play a role in LVAD-associated GI bleeding.[39,40]

Neurologic Complications

Despite advances in device design, neurologic events, including transient ischemic attacks and cerebrovascular accidents (ischemic and hemorrhagic), continue to be a significant morbidity. Kato et al[41] reported that the prevalence of neurologic events was no different between CF and older pulsatile devices (14% in each group). Backes et al[42] published a systematic review on cerebrovascular complications of LVADs and found a stroke risk of 0.25 events/patient-year with the HeartMate II LVAD. Furthermore, patients are at increased risk of ischemic and hemorrhagic stroke if they have an infection, as inflammation may imbalance endogenous coagulation mechanisms.[43]

The TAH

A small subset of patients with pronounced RV failure or other anatomic abnormality who are poor candidates for isolated LV mechanical support may benefit from total heart replacement. Examples of concomitant pathology include acute myocardial infarction with ventricular septal defect, aortic root aneurysm/dissection, cardiac allograft failure, massive ventricular thrombus, refractory malignant arrhythmias, hypertrophic/restrictive cardiomyopathy, and complex

congenital heart disease.[44] Patients often present emergently to the ICU preoperatively, and the majority of TAH implantations are done for critical cardiogenic shock or rapidly declining patients.[45]

Device Design and Parameters

The SynCardia TAH (SynCardia Systems, Inc) is, to our knowledge, the only TAH currently in clinical use and US Food and Drug Administration approved as a bridge to transplantation. The native right and left ventricles are excised and replaced with two 70-mL polyurethane pneumatic chambers. Each chamber has two mechanical tilting disc valves replicating the function of the excised cardiac valves and a pneumatically driven diaphragm. Pneumatic drivelines tunneled through the abdominal wall connect each chamber to an external driver. The driver forces air in and out through the drivelines to displace the diaphragms and circulate blood through the body (Fig 5).

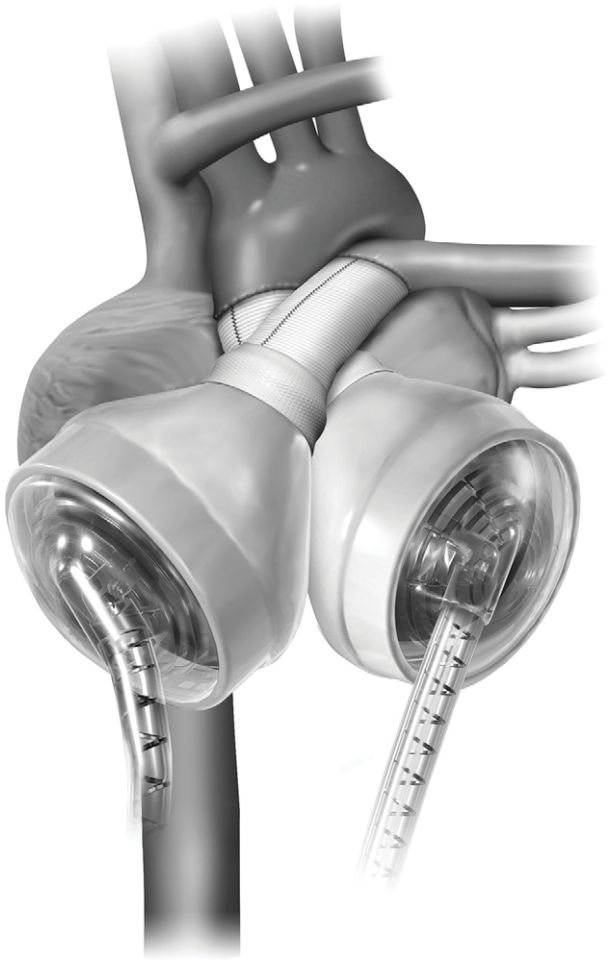

Figure 5 – *Drawing of the total artificial heart, which replaces the entire ventricular myocardium, all four valves, and the proximal portion of the great vessels. (Image provided courtesy of SynCardia Systems, Inc.)*

In contrast to the perioperative management of the patient with an LVAD, the TAH provides high cardiac output (6-8 L/min) with lower vasoconstrictor requirements and no potential for arrhythmia complications. The clinician can modify beat rate, drive pressure, percent of time in systole, and vacuum pressure to modify pump filling and ejection characteristics to optimize cardiac output. Airflow and pressure within the drivelines are graphically displayed beat to beat on the console to guide settings. To ensure constant movement of blood and minimize the potential for thrombus formation, device parameters are adjusted for "partial filling" (demonstrated as continuous airflow return at the end of systole on the flow curve) and "complete eject" (demonstrated as a small pressure spike at the end of systole on the pressure curve).

Patients generally begin IV anticoagulation and transition to oral anticoagulation, aspirin, and dipyridamole. The goal of therapy is an international normalized ratio between 2 and 3. Patients with evidence of increasing hemolysis may benefit from the addition of pentoxifylline.

TAH Complications

Perioperative complications of the TAH are unique from those observed with an LVAD. Early after device implantation, bleeding is common, and, thus, a strategy of delayed sternal closure is used at many centers. Mediastinal tamponade can compress systemic and/or pulmonary venous return, resulting in decreased pump output and persistent cardiogenic shock. Transesophageal and intracardiac echocardiography are useful modalities to assess venous return intraoperatively.

Pulmonary congestion from left-sided heart failure usually improves early after device implantation; thus, persistent pulmonary congestion after device implantation warrants further investigation. In patients with long-standing pulmonary hypertension and significant pulmonary venous remodeling, the higher RV drive pressure required for full right-sided ejection may be detrimental. It is possible to "overdrive" the right-sided output leading to profound pulmonary edema. Severe respiratory failure (inflammation or congestion) from any cause can be effectively managed with temporary venovenous extracorporeal membrane oxygenation support.

Renal failure occurs frequently after implantation of the TAH, which may be partly related to the abrupt decrease in endogenous natriuretic peptide production associated with ventricular excision. Perioperative supplementation with low-dose nesiritide infusion (0.005 μg/kg/min) appears to improve urine output and reduce the

incidence of renal failure.[46-48] However, the long-term impact of nesiritide therapy on renal function and outcomes after transplantation is unknown.

Patients with TAH demonstrate significant chronic anemia that reverses after heart transplantation.[49] Causes are believed to include low-grade hemolysis and ineffective erythropoieses possibly related to chronic inflammation. Despite the anemia, patients with TAH demonstrate acceptable exertional capacity and minimal symptoms even with hemoglobin concentrations of 5 to 6 g/dL.[50] To avoid sensitization and other associated complications, transfusions should be avoided unless the patient has significant symptoms or other end-organ dysfunction. Severe anemia requiring frequent blood transfusions should raise concern for obstruction to blood flow in one of the pumps caused by thrombosis, impingement, or tissue pannus.

Until recently, patients with TAH remained hospital bound and tethered to a 189 kg (418-pound) console. Increased waiting time for donor organs has been accompanied by significantly reduced quality of life as well as increased financial costs. A portable driver allowing discharge to home has been evaluated for clinical use and is awaiting regulatory approval for use in the United States.[51]

Future Directions for Total Heart Replacement

Considering the durability and compact size of CF LVADs, efforts have been made toward fully implanting CF biventricular assist devices. Frazier et al[52,53] developed a technique in which two axial-flow LVADs supplanted excised ventricles by replacing the inflow and outflow grafts with titanium adapters and eventually implanted two LVADs in a patient with systemic amyloidosis. Durable success has been obtained with biventricular implants of the centrifugal-flow LVADs.[54]

There are CF TAH devices in development in the United States and Europe. The Cleveland Clinic Continuous Flow Total Artificial Heart has a single direct current motor and rotating assembly affixed to two centrifugal pumps and is currently undergoing in vivo studies, bench testing, and fit studies in humans.[55] French investigators are using bioprosthetic material to design the CARMAT TAH, (CARMAT) an implantable, electro-hydraulically-driven, pulsatile-flow device with four bioprosthetic valves.[56]

Conclusions

As clinicians increasingly use mechanical circulatory devices, device technologies (and complications) will continue to evolve. Clinicians in the ICU have an impactful role in the diagnosis and treatment of MCS complications and optimization of device function.

Acknowledgments

Financial/nonfinancial disclosures: The authors have reported to *CHEST* the following conflicts of interest: Dr Shah receives institutional grants from Thoratec Corporation. Dr Malhotra receives research funding from Thoratec Corporation. Dr Kasirajan is a consultant for SynCardia Systems, Inc. Drs Smallfield, Tang, and Cooke have reported that no potential conflicts of interest exist with any companies/organizations whose products or services may be discussed in this article.

Other contributions: We thank Maureen Flattery, RN, MS, ANP, for her editorial guidance.

References

1. Kirklin JK, Naftel DC, Kormos RL, et al. Fifth INTERMACS annual report: risk factor analysis from more than 6,000 mechanical circulatory support patients. *J Heart Lung Transplant*. 2013;32(2):141-156.
2. Shah KB, Tang DG, Cooke RH, et al. Implantable mechanical circulatory support: demystifying patients with ventricular assist devices and artificial hearts. *Clin Cardiol*. 2011;34(3):147-152.
3. Feldman D, Pamboukian SV, Teuteberg JJ, et al; International Society for Heart and Lung Transplantation. The 2013 International Society for Heart and Lung Transplantation Guidelines for mechanical circulatory support: executive summary. *J Heart Lung Transplant*. 2013;32(2):157-187.
4. Moazami N, Fukamachi K, Kobayashi M, et al. Axial and centrifugal continuous-flow rotary pumps: a translation from pump mechanics to clinical practice. *J Heart Lung Transplant*. 2013;32(1):1-11.
5. Meyer AL, Kuehn C, Weidemann J, et al. Thrombus formation in a HeartMate II left ventricular assist device. *J Thorac Cardiovasc Surg*. 2008;135(1):203-204.
6. Ammar KA, Umland MM, Kramer C, et al. The ABCs of left ventricular assist device echocardiography: a systematic approach. *Eur Heart J Cardiovasc Imaging*. 2012;13(11):885-899.
7. Uriel N, Morrison KA, Garan AR, et al. Development of a novel echocardiography ramp test for speed optimization and diagnosis of device thrombosis in continuous-flow left ventricular assist devices: the Columbia ramp study. *J Am Coll Cardiol*. 2012;60(18):1764-1775.
8. Rothenburger M, Wilhelm MJ, Hammel D, et al. Treatment of thrombus formation associated with the MicroMed DeBakey VAD using recombinant tissue plasminogen activator. *Circulation*. 2002;106(12 suppl 1):I189-I192.
9. Moazami N, Milano CA, John R, et al; HeartMate II Investigators. Pump replacement for left ventricular assist device failure can be done safely and is associated with low mortality. *Ann Thorac Surg*. 2013;95(2):500-505.
10. Stulak JM, Cowger J, Haft JW, Romano MA, Aaronson KD, Pagani FD. Device exchange after primary left ventricular assist device implantation: indications and outcomes. *Ann Thorac Surg*. 2013;95(4):1262-1267.
11. Sorensen EN, Hiivala NJ, Jeudy J, Rajagopal K, Griffith BP. Computed tomography correlates of inflow cannula malposition in a continuous-flow ventricular-assist device. *J Heart Lung Transplant*. 2013;32(6):654-657.
12. Raman SV, Sahu A, Merchant AZ, Louis LB IV, Firstenberg MS, Sun B. Noninvasive assessment of left ventricular assist devices with cardiovascular computed tomography and impact on management. *J Heart Lung Transplant*. 2010;29(1):79-85.
13. Shah KB, Kontos MC, Parker MS, Kasirajan V. A crescendo-decrescendo murmur and lightheadedness in a patient with a left ventricular assist device. *J Am Coll Cardiol*. 2013;61(24):2484.
14. John R, Mantz K, Eckman P, Rose A, May-Newman K. Aortic valve pathophysiology during left ventricular assist device support. *J Heart Lung Transplant*. 2010;29(12):1321-1329.
15. Atkins BZ, Hashmi ZA, Ganapathi AM, et al. Surgical correction of aortic valve insufficiency after left ventricular assist device implantation. *J Thorac Cardiovasc Surg*. 2013;146(5):1247-1252.

16. Kormos RL, Teuteberg JJ, Pagani FD, et al; HeartMate II Clinical Investigators. Right ventricular failure in patients with the HeartMate II continuous-flow left ventricular assist device: incidence, risk factors, and effect on outcomes. *J Thorac Cardiovasc Surg*. 2010;139(5):1316-1324.
17. Farrar DJ, Compton PG, Hershon JJ, Fonger JD, Hill JD. Right heart interaction with the mechanically assisted left heart. *World J Surg*. 1985;9(1):89-102.
18. Krohn CD, Reikerås O, Mollnes TE. Complement activation and increased systemic and pulmonary vascular resistance indices during infusion of postoperatively drained untreated blood. *Br J Anaesth*. 1999;82(1):47-51.
19. Fitzpatrick JR III, Frederick JR, Hsu VM, et al. Risk score derived from pre-operative data analysis predicts the need for biventricular mechanical circulatory support. *J Heart Lung Transplant*. 2008;27(12):1286-1292.
20. Matthews JC, Koelling TM, Pagani FD, Aaronson KD. The right ventricular failure risk score a pre-operative tool for assessing the risk of right ventricular failure in left ventricular assist device candidates. *J Am Coll Cardiol*. 2008;51(22):2163-2172.
21. Atluri P, Goldstone AB, Fairman AS, et al. Predicting right ventricular failure in the modern, continuous flow left ventricular assist device era. *Ann Thorac Surg*. 2013;96(3):857-863.
22. Grant ADM, Smedira NG, Starling RC, Marwick TH. Independent and incremental role of quantitative right ventricular evaluation for the prediction of right ventricular failure after left ventricular assist device implantation. *J Am Coll Cardiol*. 2012;60(6):521-528.
23. Antoniou T, Prokakis C, Athanasopoulos G, et al. Inhaled nitric oxide plus iloprost in the setting of post-left assist device right heart dysfunction. *Ann Thorac Surg*. 2012;94(3):792-798.
24. Tedford RJ, Hemnes AR, Russell SD, et al. PDE5A inhibitor treatment of persistent pulmonary hypertension after mechanical circulatory support. *Circ Heart Fail*. 2008;1(4):213-219.
25. Saeed D, Kidambi T, Shalli S, et al. Tricuspid valve repair with left ventricular assist device implantation: is it warranted? *J Heart Lung Transplant*. 2011;30(5):530-535.
26. Schaffer JM, Arnaoutakis GJ, Allen JG, et al. Bleeding complications and blood product utilization with left ventricular assist device implantation. *Ann Thorac Surg*. 2011;91(3):740-747.
27. Hannan MM, Husain S, Mattner F, et al; International Society for Heart and Lung Transplantation. Working formulation for the standardization of definitions of infections in patients using ventricular assist devices. *J Heart Lung Transplant*. 2011;30(4):375-384.
28. Goldstein DJ, Naftel D, Holman W, et al. Continuous-flow devices and percutaneous site infections: clinical outcomes. *J Heart Lung Transplant*. 2012;31(11):1151-1157.
29. Nienaber J, Wilhelm MP, Sohail MR. Current concepts in the diagnosis and management of left ventricular assist device infections. *Expert Rev Anti Infect Ther*. 2013;11(2):201-210.
30. Holman WL, Park SJ, Long JW, et al; REMATCH Investigators. Infection in permanent circulatory support: experience from the REMATCH trial. *J Heart Lung Transplant*. 2004;23(12):1359-1365.
31. Suarez J, Patel CB, Felker GM, Becker R, Hernandez AF, Rogers JG. Mechanisms of bleeding and approach to patients with axial-flow left ventricular assist devices. *Circ Heart Fail*. 2011;4(6):779-784.
32. Aggarwal A, Pant R, Kumar S, et al. Incidence and management of gastrointestinal bleeding with continuous flow assist devices. *Ann Thorac Surg*. 2012;93(5):1534-1540.
33. Vincentelli A, Susen S, Le Tourneau T, et al. Acquired von Willebrand syndrome in aortic stenosis. *N Engl J Med*. 2003;349(4):343-349.
34. Uriel N, Pak S-W, Jorde UP, et al. Acquired von Willebrand syndrome after continuous-flow mechanical device support contributes to a high prevalence of bleeding during long-term support and at the time of transplantation. *J Am Coll Cardiol*. 2010;56(15):1207-1213.
35. Crow S, Chen D, Milano C, et al. Acquired von Willebrand syndrome in continuous-flow ventricular assist device recipients. *Ann Thorac Surg*. 2010;90(4):1263-1269.
36. Wever-Pinzon O, Selzman CH, Drakos SG, et al. Pulsatility and the risk of nonsurgical bleeding in patients supported with the continuous-flow left ventricular assist device HeartMate II. *Circ Heart Fail*. 2013;6(3):517-526.
37. Rennyson SL, Shah KB, Tang DG, et al. Octreotide for left ventricular assist device-related gastrointestinal hemorrhage: can we stop the bleeding? *ASAIO J*. 2013;59(4):450-451.
38. Szilagyi A, Ghali MP. Pharmacological therapy of vascular malformations of the gastrointestinal tract. *Can J Gastroenterol*. 2006;20(3):171-178.
39. Krikis N, Tziomalos K, Perifanis V, et al. Treatment of recurrent gastrointestinal haemorrhage in a patient with von Willebrand's disease with octreotide LAR and propranolol. *Gut*. 2005;54(1):171-172.
40. Bowers M, McNulty O, Mayne E. Octreotide in the treatment of gastrointestinal bleeding caused by angiodysplasia in two patients with von Willebrand's disease. *Br J Haematol*. 2000;108(3):524-527.
41. Kato TS, Schulze PC, Yang J, et al. Pre-operative and post-operative risk factors associated with neurologic complications in patients with advanced heart failure supported by a left ventricular assist device. *J Heart Lung Transplant*. 2012;31(1):1-8.
42. Backes D, van den Bergh WM, van Duijn AL, Lahpor JR, van Dijk D, Slooter AJC. Cerebrovascular complications of left ventricular assist devices. *Eur J Cardiothorac Surg*. 2012;42(4):612-620.
43. Aggarwal A, Gupta A, Kumar S, et al. Are blood stream infections associated with an increased risk of hemorrhagic stroke in patients with a left ventricular assist device? *ASAIO J*. 2012;58(5):509-513.
44. Thanavaro KL, Tang DG, Cooke RH, et al. Characteristics and survival of patients with the total artificial heart implanted for indications other than biventricular failure. *J Heart Lung Transplant*. 2013;32(4):S231.
45. Shah KB, Thanavaro KL, Tang DG, Kasirajan V. Clinical outcomes for INTERMACS Profile 1 patient implanted with the total artificial heart. *J Heart Lung Transplant*. 2013;32(4):S236.
46. Stribling WK, Shah KB, Gunnerson KJ, et al. 273 Use of nesiritide and renal function following total artificial heart implantation. *J Heart Lung Transplant*. 2011;30(4):S96.
47. Delgado R III, Wadia Y, Kar B, et al. Role of B-type natriuretic peptide and effect of nesiritide after total cardiac replacement with the AbioCor total artificial heart. *J Heart Lung Transplant*. 2005;24(8):1166-1170.
48. Shah KB, Tang DG, Kasirajan V, Gunnerson KJ, Hess ML, Sica DA. Impact of low-dose B-type natriuretic peptide infusion on urine output after total artificial heart implantation. *J Heart Lung Transplant*. 2012;31(6):670-672.
49. Mankad AK, Tang DG, Clark WB, et al. Persistent anemia after implantation of the total artificial heart. *J Card Fail*. 2012;18(6):433-438.
50. Kohli HS, Canada J, Arena R, et al. Exercise blood pressure response during assisted circulatory support: comparison of the total artificial [corrected] heart with a left ventricular assist device during rehabilitation. *J Heart Lung Transplant*. 2011;30(11):1207-1213.
51. Jaroszewski DE, Anderson EM, Pierce CN, Arabia FA. The SynCardia freedom driver: a portable driver for discharge home with the total artificial heart. *J Heart Lung Transplant*. 2011;30(7):844-845.
52. Frazier OH, Cohn WE, Tuzun E, Winkler JA, Gregoric ID. Continuous-flow total artificial heart supports long-term survival of a calf. *Tex Heart Inst J*. 2009;36(6):568-574.
53. Frazier OH, Cohn WE. Continuous-flow total heart replacement device implanted in a 55-year-old man with end-stage heart failure and severe amyloidosis. *Tex Heart Inst J*. 2012;39(4):542-546.
54. Krabatsch T, Potapov E, Stepanenko A, et al. Biventricular circulatory support with two miniaturized implantable assist devices. *Circulation*. 2011;124(11 suppl):S179-S186.
55. Fumoto H, Horvath DJ, Rao S, et al. In vivo acute performance of the Cleveland Clinic self-regulating, continuous-flow total artificial heart. *J Heart Lung Transplant*. 2010;29(1):21-26.
56. Jansen P, van Oeveren W, Capel A, Carpentier A. In vitro haemocompatibility of a novel bioprosthetic total artificial heart. *Eur J Cardiothorac Surg*. 2012;41(6):e166-e172.