Chapter 21
Right Ventricular Assist Devices

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Introduction

Acute decompensated right heart failure (ADRFH) often proves refractory to medical therapy that includes measures such as pulmonary vasodilators, systemic vasopressors, and inotropes (see also Chap. 10) oxygen therapy and (where appropriate) balloon atrial septostomy. In this chapter, we will discuss the use of mechanical circulatory support devices (MCSD) to sustain the failing right ventricle (RV). We will focus in particular on the role of extracorporeal life support (ECLS) and innovative device therapies in patients with pulmonary hypertension (PH), most of whom are candidates for bridge to transplant (and occasionally bridge to recovery) strategies.

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Mechanical Circulatory Support Options for the Failing Right Ventricle Vary by Clinical Scenario

Broadly defined as impaired RV filling or emptying in the absence of overt heart failure (HF) symptoms [1], RV dysfunction arises in the setting of concomitant left ventricular (LV) dysfunction, cardiomyopathies, lung disease, congenital heart disease, PH, and hepatic failure [2, 3]. RV failure is typically characterized by a combination of low cardiac output and elevated central venous pressures (CVP) [4], and elevated RV end diastolic pressure (EDP) [3], underfilling of the LV and variable LVEDP, which clinically can manifest with systemic hypotension, fatigue, organ hypoperfusion, peripheral edema, and ascites [5]. If left untreated, RV failure can lead to end-organ damage, including renal and/or hepatic failure and death.

The initial goals of management of the patient with RV failure are to optimize RV preload, contractility, and afterload [6]. Both hypervolemia and hypovolemia can challenge RV function and reduce cardiac output [6, 7]. Volume removal strategies include diuresis and ultrafiltration [3, 6]. Vasopressors such as norepinephrine and vasopressin can be used to maintain systemic pressures above pulmonary arterial pressures [6, 7]. Intravenous prostacyclins such as epoprostenol and treprostinil, as well as inhaled therapies such as nitric oxide (iNO), iloprost, treprostinil, and even inhaled milrinone can reduce pulmonary vascular resistance (PVR) and RV afterload [7].

For RV dysfunction refractory to medical therapy including inotropes, RV assist devices (RVADs) may be considered [6]. RVADs have traditionally been used to support the RV after acute myocardial infarction (MI), myocarditis, or in the setting of post-cardiac surgery RV failure, such as after cardiotomy, in acute or chronic rejection after heart transplant, or after left ventricular assist device implantation (LVAD) [5–7]. Adverse events include thromboembolism, bleeding, and infection [3]. In select cases with appropriate therapy and support, RV dysfunction tends to be more reversible than left sided failure [2], permitting shorter duration of support. But while RV failure remains a long-term sequela of device therapy in a subset of patients with LVADs as "destination therapy," there are currently no devices in the United States approved for long-term support for persistent RV failure [8].

In patients with fulminant myocarditis, or after cardiotomy and LVAD implantation, biventricular support is associated with worse outcomes, in part related to increased severity of disease with manifestations of multiorgan system dysfunction [3]. In particular, the prevalence of RV failure after LVAD implantation is estimated at greater than 40 % [8, 9] and mortality is greater than 70 % [9]. RV volume and wall stress increase postoperatively, as the LV is decompressed and the septum shifts leftward [4, 8]. In select patients, preemptive RVAD at the time of LVAD implantation has been shown to lead to better outcomes in terms of survival to discharge and 1 year survival [10].

In general, although virtually all patients have echocardiographic manifestations of RV dysfunction after LVAD implantation, the incidence of frank acute RV failure requiring device therapy has diminished with increasing use of continuous-flow devices as compared to pulsatile devices and with more aggressive medical therapy.

While there are a multitude of risk profiles to predict the need for RVADs, some of the simplest preoperative characteristics include signs of hepatic congestion (aspartate aminotransferase AST > 80 U/L and bilirubin > 2 mg/dL) creatinine > 2.3 mg/dL [11], blood urea nitrogen (BUN) > 39 [12], and a CVP/pulmonary capillary wedge pressure (PCWP) ratio > 0.63 [12].

In those patients with PH and medically refractory RV failure, RVADs should be cautiously considered as there is at least a theoretical risk that the high flow and pressure generated in a remodeled pulmonary vascular bed may damage the pulmonary microcirculation [6] and lead to pulmonary hemorrhage [13]. Newer continuous-flow pumps may be safer in this regard. ECLS, which incorporates an oxygenator blood pump, provides an alternative route to maintain cardiac output in a patient with a failing RV [7] while minimizing this risk [6]. This will be addressed in the ECLS section. Thus, approaches to device therapy in the setting of chronic RV failure need to be distinct from those in the biventricular heart failure population and must be individualized based on the pathology.

RVAD Design Innovations Focus on Miniaturization and Blood Compatibility

Compared to LVADs, RVADs face much lower hydraulic loads and require lower power [8]. On average, the devices must generate between 2 and 6 L/min of flow, with a pump pressure between 20 and 50 mmHg [8]. To meet these requirements, modifications to LVADs include outlet banding that increases resistance to flow [8], constrictors [14], lower pump speed [9], and the use of spacers to shorten inflow cannulas that are placed in the RV [14]. Such adaptations minimize the risk of pulmonary overcirculation, ventricular suction events, and thrombosis [8].

Inflow cannulas can be placed in either the right atrium (RA) or RV. RV cannulation maximizes RV unloading and reduces thrombus risk in severe dysfunction when there is little expectation of recovery [15]. However, it has been associated with higher scar formation and suction events compared to LV cannulation [8]. If temporary support is required, RA cannulation [8] might allow for higher rates of pulmonary valve opening, lower RV stroke work, and eventual RV recovery [15]. However, RA cannulation has also been used in pulsatile devices for longer support as a bridge to transplantation [8].

Both pulsatile and continuous-flow devices are currently used for RV support. Unlike pulsatile devices, continuous-flow assist devices empty the ventricle in both systolic and diastole [8]. They are smaller and contain fewer moving parts compared to pulsatile devices, with improved durability [8]. However, with decreased sensitivity to preload, continuous-flow devices are more susceptible to suction events [8].

Concerns about infection risk, quality of life, hemolysis, and thrombosis have traditionally caused delays in referral for RV support [9] and are being addressed in more recent device designs. Solutions currently under evaluation include miniaturization, percutaneous approaches, and contactless suspension that reduce the surface

area exposed to blood and a control system then enables long-term support and ambulation [9].

RVADs Vary in Terms of Implantation Technique, Flow Rates, and Complications

MCSD are available in configurations ranging from extracorporeal, in which the pumps are external to the body and connected via cannulas that are tunneled out of the body, to implantable, in which the pumps are internal with only a control cable tunneled out of the body. Technologies have evolved from pulsatile pumps that are either electrically or pneumatically driven to continuous-flow pumps that work via an inline turbine or a centrifugally oriented rotor. For support of the left ventricle, most pumps utilized today are continuous-flow pumps due to the smaller size and greater device longevity. However, many of these newer devices are not yet approved for RV or biventricular support.

Extracorporeal Support

Extracorporeal pumps are designed for short-term mechanical support. They have typically been used in critically ill patients who have developed RV failure after cardiac surgery (cardiotomy, transplantation, and/or LVAD). Outcomes are generally poor but better than would otherwise be expected in such cases of multiorgan failure and reflects the inherent high risk in this population [16–19].

Surgically Implanted Extracorporeal Devices

The centrifugal continuous-flow pump Centrimag® (Levitronix LLC, Waltham, MA, USA) is the only FDA-approved extracorporeal device for RV support [3]. It uses a magnetic suspended impeller [3, 9] (Fig. 21.1a) and can be used for up to 30 days of support [3]. The lack of bearings and seals minimizes friction and wear over time, thus reducing thermal damage to blood cells and lowering rates of hemolysis and thrombosis [16]. In a retrospective review of 29 patients, this pump was used for the treatment of RV failure after cardiotomy, transplantation, and LVAD implantation. The mean duration of support was 8.8 days, with 70 % of the transplant and 58 % of the LVAD patients successfully weaned off support. The 30-day mortality was 48 % [16].

By contrast, the Biomedicus® (Medtronic Inc., Minneapolis, MN, USA) continuous-flow pump [9] (Fig. 21.1b) has higher rates of hemolysis [4] and platelet damage [16]. Other adverse events include bleeding and thromboembolism [4]. In a retrospective review of 141 patients who required RV support after valve surgery, coronary artery bypass grafting (CABG) or aortic surgeries, the Biomedicus® pump was used in eight patients for isolated RV support and 23 for biventricular support [17]. The duration of support ranged from 1 to 7 days for patients with
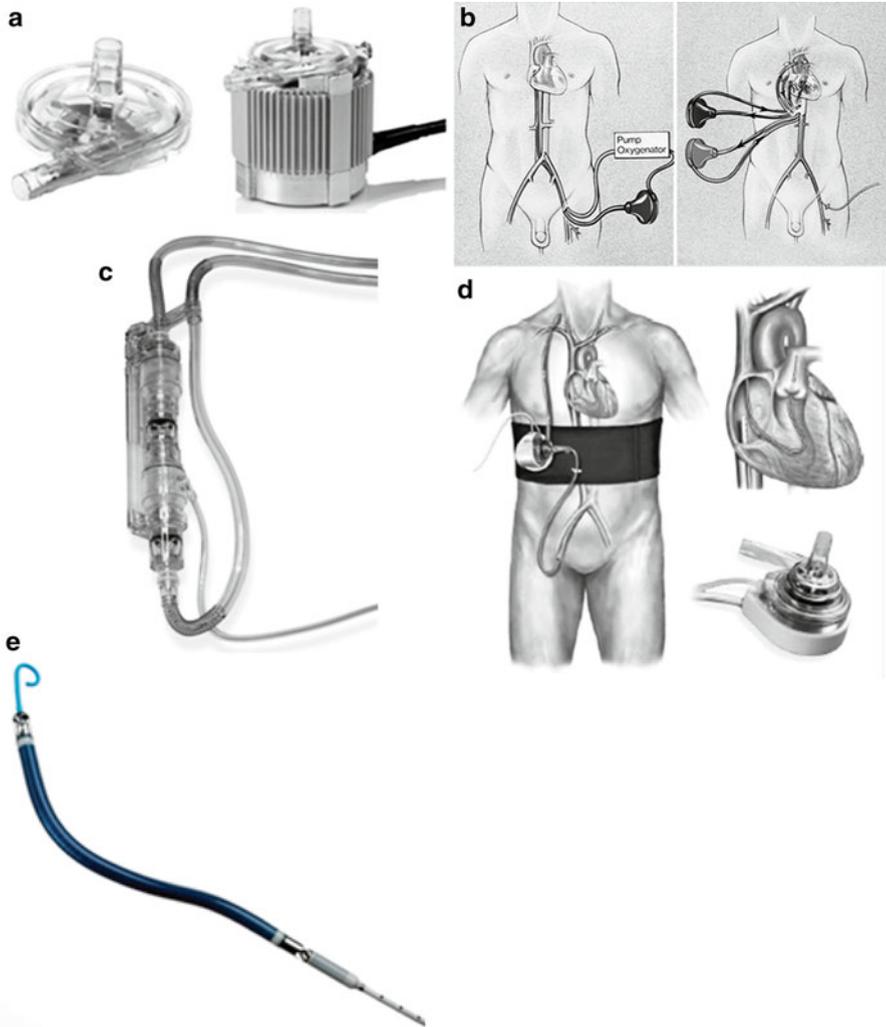
Fig. 21.1 Extracorporeal RV assist devices. (**a**) Centrimag impeller and pump (video by Thoratec Corp.). (**b**) BioMedicus pump and circuits for RV support alone (*left*) and biventricular support (*right*). Adapted with permission from Noon et al. [17]. (**c**) Abiomed BVS 5000 (video by Abiomed Inc.). (**d**) TandemHeart circuit. Two configurations, one with outflow cannula in jugular vein (*left*) and the other with cannulae in the right heart and PA (*right*). Adapted with permission from CardiacAssist Inc. (**e**) Impella RP (video by Abiomed Inc.)

RVAD alone, and from 1 to 22 days for biventricular support. Only one RVAD patient was successfully weaned off support, and eight off biventricular support [17].

A pulsatile device, the BVS 5000® (Abiomed, Inc.) requires a sternotomy as the outflow graft must be anastamosed end to side to the main PA (Fig. 21.1c) [9]. It is a large device that significantly restricts mobility and requires re-operation to remove [9]. A retrospective review [18] of 71 patients who received this pump

showed that 22 received it for biventricular support and 30 for RVAD alone. Cases included RV failure after CABG and valve surgery, transplantation, LVAD implantation, acute MI, myocarditis, and refractory ventricular arrhythmia. The mean duration of support was 5.3 ± 4.2 days for RVADs and 5.1 ± 44 days for biVADs. Fifty percent of patients receiving an RVAD and 36.4 % of those who received a biVAD died [18].

Percutaneously Implanted Extracorporeal Devices

Both devices that are currently available for percutaneous implantation are indicated for short-term use, only. The TandemHeart™ (CardiacAssist Inc., Pittsburgh, PA, USA) percutaneous ventricular assist device (pVAD) is a centrifugal continuous-flow pump which can be adapted to provide RV support [2, 3]. The RA and pulmonary artery (PA) [2] are cannulated (Fig. 21.1d), with percutaneous access obtained via the femoral vein. A recent review [19] included 46 patients in whom the pVAD (percutaneous and surgical approach) was used for isolated RV as well as biventricular support. Cases included acute MI, myocarditis, chronic LV dysfunction, and patients post valve and CABG surgery. The mean duration of support was 4.8 ± 6.1 days for the percutaneous approach, and 6.5 ± 6.2 days for the surgical approach. Mean flow provided was 4.2 ± 1.3 L/min. Overall in-hospital mortality was 57 %, with cause of death being multiorgan failure [19].

An axial continuous-flow pump, the Impella RP can also provide RV support [3] with flows up to 4.8 L/min [2]. It is a small device, with a diameter of 6.4 mm and weight of 17 g, which permits both percutaneous and central approaches for implantation (Fig. 21.1e) [9]. The inlet cannula is placed in the inferior vena cava (IVC) and outflow in the PA [2]. Advantages over the Centrimag and AB5000 include a much smaller surface area exposed to blood [2], but the device relies on mechanical bearings which increase the risk of hemolysis and thrombosis [9]. As a result, it is presently approved for only 10 days of support [9]. In first-in-man trials in Canada and Europe, the device has been used in patients with RV failure after cardiac surgery and after LVAD implantation. The duration of support has ranged from 1 to 7 days, with >60 % of patients being supported for more than 4 days and having the device explanted upon recovery of the RV [2, 20].

Paracorporeal Support

The options for paracorporeal support are comprised of pneumatic pulsatile devices. Of these, only the Thoratec PVAD (Thoratec Corp., Pleasanton, CA, USA) has been approved by the FDA for RV support [3]. As a bridge to transplantation and recovery [3, 9], it has been used for univentricular or biventricular support in over 4,000 patients since 2010 (Fig. 21.2a) [4]. In general, biventricular support has worse outcomes than LV support alone [21] and planned biventricular support is
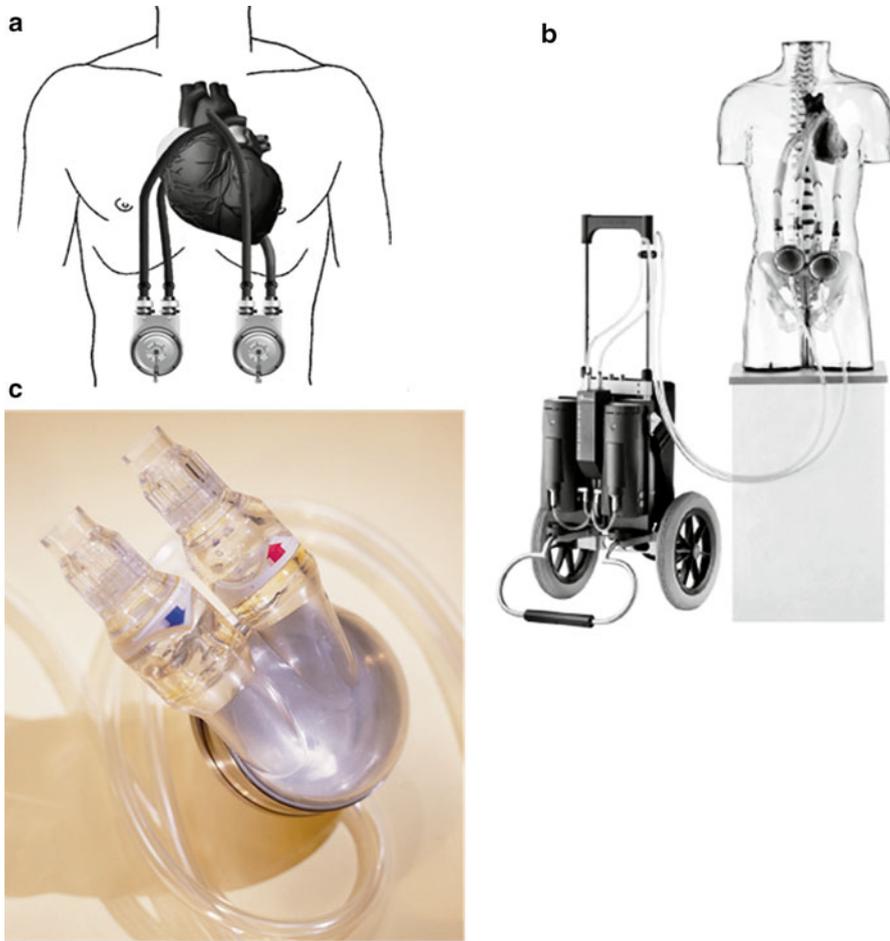
Fig. 21.2 Paracorporeal RV assist devices. (**a**) Thoratec PVAD, biventricular support model (video by Thoratec Corp.). (**b**) Abiomed AB5000 ventricle (video by Abiomed Inc.). (**c**) BerlinHeart Excor in biventricular configuration with driver allowing ambulatory support (video by BerlinHeart GmbH)

associated with better outcomes than LVAD implantation followed by RV failure requiring a second operation for RVAD implantation [10]. Single center experience with biventricular support using the Thoratec PVAD has reported survival rates of 75 % when excluding those supported for postcardiotomy or post-infarct shock which is known to have very poor outcomes [22].

The AB5000 (Abiomed Inc.) requires a sternotomy to cannulate the RA and PA [16], but the device can be exchanged at the bedside without a re-operation [9]. Duration of support can last up to months [16]. It can generate flows of up to 5–6.5 L/min, and has a fixed drive pressure of 300 mmHg (Fig. 21.2b) [4]. Introduced in 1988 [23], the BerlinHeart Excor (Berlin Heart GmbH) device can be used as a

bridge to recovery or transplantation [4]. It can provide ambulatory support for up to 10 h [9], and has been demonstrated to provide biventricular support for up to 575 days (Fig. 21.2c) [23].

Implantable Devices

The pulsatile Thoratec IVAD™ (Thoratec Corp., Pleasanton, CA, USA) [3] can provide intermediate to long-term support and is indicated for biventricular support as a bridge to transplant or recovery (Fig. 21.3a) [9]. In a multicenter clinical trial of 29 patients, 15 received biventricular support using the IVAD. Of the 14 bridge to transplant candidates, eight patients survived: one was weaned off support, and the other seven were transplanted [24].

Continuous-flow devices such as the HVAD® (HeartWare International Inc., MA, USA) and HeartMate II® (Thoratec Corp., Pleasanton, CA, USA) have been used to provide biventricular support [9] in cases such as giant cell myocarditis [25] and after cardiac arrest during non-cardiac surgery [26]. With dual controllers, the Heartware system has been increasingly used as an alternative to the total artificial heart. Such dual support can provide successful physiologic levels of support and can alter flows to respond to changes in preload and afterload [26]. The duration of support has ranged from 7 days [26] to 4 months [25]. Complications include suction events causing RA collapse [26]. Although these devices are not approved by the FDA for RV support, they have been used for RV support in Europe and in the United States (via individual appeals to the FDA for Humanitarian Device Exemption), utilizing separate controllers and certain adaptations by some centers. With such biventricular support, RVAD flows have been set lower than systemic output, to avoid overloading the LV [8].

However, some investigators point out that adapting LVADs for RV support—specifically by reducing pump speeds beyond design specifications—increases thrombosis risk [8]. A continuous-flow pump designed specifically for the RV, the Cleveland Clinic's DexAide RVAD has been successfully implanted in calves and averaged 24 ± 21 days of support, generating flows of 5.4 ± 1 L/min [8, 9]. In animal models of biventricular support using continuous-flow devices, these investigators have found that the circulatory loop is most stable when RVAD flows are lower than the LVAD's [8]. Specifically, in a biventricular support model, RVAD speeds must ideally (1) adjust so that flows match 50–75 % of the LVAD output at any point in time and (2) have a maximum threshold so that, in the event of hypovolemia or LV failure, the system can avoid suction events and overdriving [8].

The Circulite® Synergy® micropump has similarly been used for biventricular support in fibrillating sheep hearts [14]. This miniature pump, which weighs 25 g, has a pressure gradient of 70–80 mmHg and can generate flows up to 4.25 L/min. Lower flow rates of 3 L/min can be generated at the lowest speed of 20,000 rpm and a pressure gradient of 30 mmHg, which make it ideal for RV support (Fig. 21.3b) [14]. In the fibrillating heart model, right and left sided flows always equilibrated,

Fig. 21.3 Implantable RV assist devices. (**a**) Thoratec IVAD (video by Thoratec Corp). (**b**) Circulite device configured for RV support (video by Daniel Bukhoff)
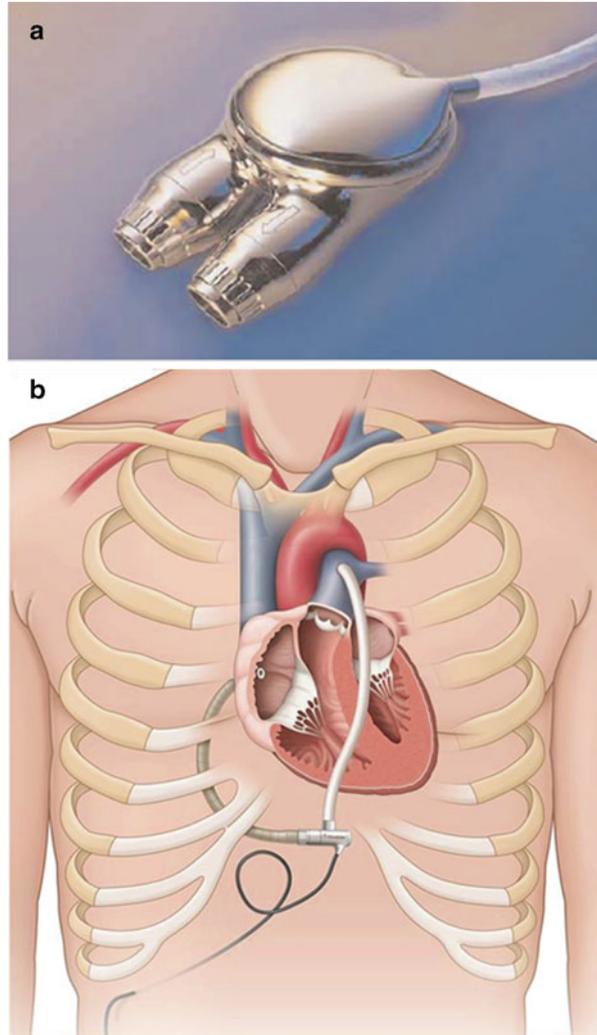
with a proportional decrease in left atrial (LA)-aorta pressure gradient if the RA-PA gradient were increased with increasing RVAD speeds [14]. The Circulite system is currently undergoing revision.

Low Flow RVAD in PH Disease Models

There is potentially a great need for RV support in pulmonary arterial hypertension (PAH), as many patients die from RV failure (see Chap. 14). RV dysfunction in the setting of PAH or pulmonary veno-occlusive disease poses a significant challenge
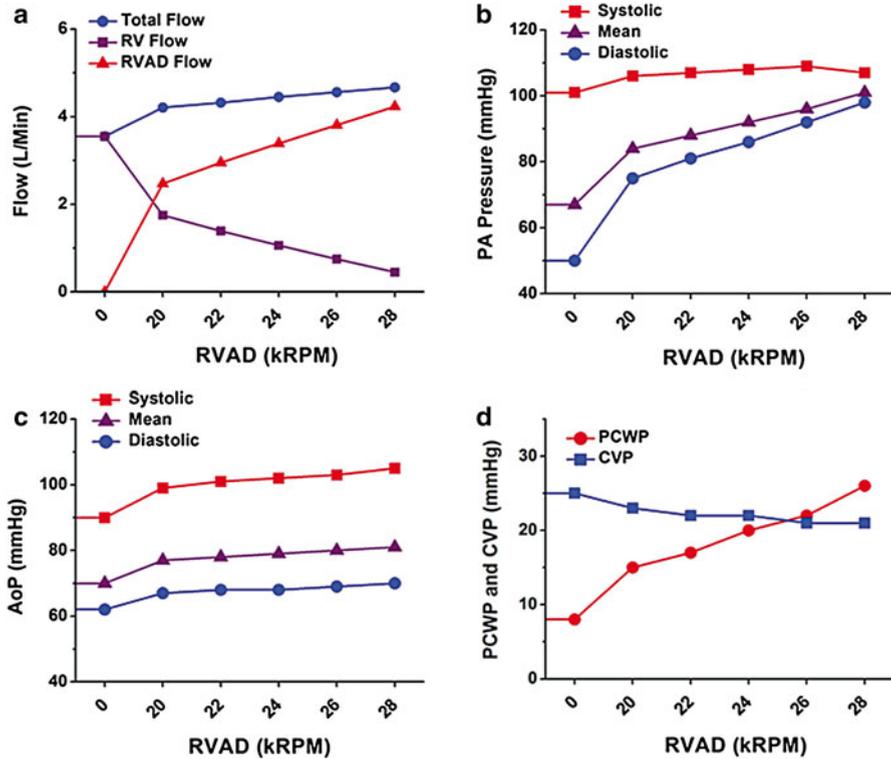
Fig. 21.4 Simulated case of severe pulmonary arterial hypertension with incorporation of right sided mechanical support device. (**a**) Total output compared to RV and device flows. (**b**) PA systolic, diastolic, and mean pressures. (**c**) Aortic systolic, diastolic, and mean pressures. (**d**) Wedge and central venous pressures. (video by Punnoose et al. [27])

for mechanical support, as the RV pump failure is also accompanied by significant LV diastolic dysfunction [27]. Case reports of patients in florid cardiogenic shock have also described significantly elevated pulmonary pressures with and without associated pulmonary hemorrhage after RVAD implantation [13, 28]. Indeed, a computer simulation of the cardiovascular system in PAH and RV dysfunction incorporating a continuous-flow micropump showed that, while left sided filling and cardiac output improved with mechanical support, pulmonary arterial pressures and PCWP rose significantly [27]. However, the increase in pulmonary arterial pressures could be mitigated by setting lower RVAD flow rates with continued improvement of the systemic hemodynamics (Fig. 21.4) [27].

Such a system has been shown to be feasible in animal models. One such device is the OxyRVAD, which generates flows of up to 3 L/min through the pulmonary vascular bed [29]. It includes both an axial flow pump and a low resistance gas exchanger, with the VAD cannula placed in the RA appendage and the outflow graft anastamosed to the PA. The device successfully provided hemodynamic support for 14 days in healthy sheep [29]. The MC3 BioLung is a thoracic artificial lung (TAL)

that has been studied in sheep models with chronic PH [30]. The circuit connects the PA and LA, and it does not (yet) incorporate a blood pump. The total impedance of the TAL in parallel with the native pulmonary circulation is less than the native system alone, thus decreasing pulmonary resistance and RV afterload. More blood can be diverted to the TAL when the PA is banded, but this is at the expense of increased overall impedance and afterload. The systemic output drops when >75 % of blood flow is diverted to the TAL [30].

More recently, the successful use of a paracorporeal artificial lung (PAL) has been described in patients with PH and RV failure [31, 32]. The Novalung, which does not incorporate a blood pump, connects the PA and LA and has been demonstrated to generate flows of 3.5 L/min, reduce PA pressures, and improve systemic hemodynamics [31]. In a retrospective review of patients with PAH who were listed for lung transplantation, the incorporation of ECLS strategy with select patients receiving the Novalung, was shown to reduce mortality and time on the waiting list for transplantation [33].

Extracorporeal Life Support (ECLS)

Similar to the initiation of support for the left heart as a bridge to transplant in INTERMACS 1 and/or 2 patients [34], several institutions have utilized the markedly improved technology of ECLS in the PH patient population awaiting lung transplant as a bridge to transplant or less commonly, as a bridge to recovery as the best means of support for the ultimate failing RV [33, 35–37]. In a newer paradigm of RV support, whereas the RVAD may ultimately be considered in the chronically failing patient (Fig. 21.4), extracorporeal membrane oxygenation (ECMO) support is the choice for the "crash and burn" viable, transplantable, "PH INTERMAS 1 and 2" equivalent in the setting of PH and RV failure. Timing is crucial—to intervene in the patient with imminent but not end-organ injury generally characterized by inotrope dependence or resistance, diuretic resistance, systemic hypotension with renal insufficiency and/or abnormal liver function tests. In particular, transfer of patients to centers where cardiac support device therapies have been established in a timely fashion is advisable. ECLS may include traditional femoral [38] vs. upper torso ambulatory "Sport Model" configurations [39] for VA or VAV ECMO circuits, single catheter VV configurations across existing intracardiac shunts [39] for effective VA support, attempts at VV with larger natural or created PFO configurations and PA-LA Novalung configurations [33].

Novalung

Extracorporeal AV removal of CO_2 can be accomplished with newer generations of low resistance membrane oxygenators (Avecor, Quadrox-D, Novalung) and smaller canulas [40]. The pumpless interventional lung assist Novalung has been used in this

setting most frequently in Hannover, Germany and Toronto, Canada. It is a low resistance device which can be connected as an AV circuit and perfused by approximately 20 % of the cardiac output [41]. Developments of the low resistance exchange membrane and a biocompatible heparin/albumin coating has permitted prolonged pumpless lung support which is driven by the patient's cardiac output with maintained pulsatile flow. While the Novalung does not require a pump for CO_2 removal, a centrifugal pump is added into the circuit in hypoxic patients. In some a VV circuit with left atrial decompression (LAD) and centrifugal pump has been used to support BTT patients for several weeks. Support for PAH patients who are dying from RV failure necessitates both support of the heart and gas exchange with effective RV unloading. Furthermore, the Novalung pulmonary artery to left atrium pumpless configuration effectively unloads the RV, bypasses the venous occlusion and may be the most effective support for the patient with PVOD. The underlying pulmonary hypertension allows for sufficient generated force in the pulmonary artery to function as the driving force for the system [41] along with a canula size which is a determining factor of flow. The oxygenator circuit is placed in parallel to the native pulmonary circuit and overall PVR is thus decreased. There are institutions that prefer this mechanical support to that of long-term ECMO configurations although most often a temporary peripheral ECMO is placed for hemodynamic stabilization prior to LAD central implantation. Earlier reports included parallel circuits to be assured of patency but device exchanges have been performed without problems for patients who are awaiting transplant for weeks.

Extracorporeal Cardiopulmonary Support (ECMO)

Traditional ECMO support began as early as 1930 with a roller pump in the setting of massive pulmonary embolic events. Countless contributions and collaborative efforts to deal with issues such as massive hemolysis, plasma leakage, artificial lung technology, membrane oxygenators, prolonged bypass support, and silicone membrane oxygenator have paved the wave to our modern use of it. Dr. Robert Bartlett is responsible for bringing this technology to the neonates [42] and the onset of its burgeoning success in the neonatal ICU. The introduction of ECMO in adult patients has been much slower. Not until the CESAR UK trial as a regionalized ECMO approach and one that utilized a VV approach, was there any success in adult respiratory failure patients. Coincident with its development was the worldwide H1N1 pandemic and need for specialized centers which could provide ECMO support for primary respiratory failure in previously healthy patients. In the current era, innovations in cannula design, next generation centrifugal pump technology, membrane construction, and now anticoagulation protocols have demonstrated the feasibility of prolonged support with a durable device. It was essential to eliminate the massive transfusion requirements and risks of hemorrhage previously inherent in adult ECMO support. Further developments of upper body ECMO, extubation, and physical therapy on support have markedly changed the outcomes of patients awaiting

lung transplantation on ECMO support [43]. ECMO may, in fact, improve the pre-transplant patient's status by allowing physical therapy, conditioning, nutrition, improvement of end-organ perfusion to allow for better post transplant outcomes. Cannulation techniques and ECMO configurations may vary with either peripheral or central cannulation, ECMO configurations with may be VV, VA, VAV, or pulmonary artery to left atrium. Traditional concerns of femoral cannulation include both a decreased upper extremity and importantly cerebral oxygenation, for which we require monitoring of upper extremity arterial saturation and the need for antegrade superficial femoral perfusion catheter due to risk of limb ischemia and lack of mobilization. Introduction of a Dacron graft as an end to side anastomosis into the distal subclavian artery and placement of a tunneled cannula into the graft protects the upper limb and avoids direct cannulation of the subclavian artery coupled with a right internal jugular venous drainage "Sport model" catheter allows for early ambulation on ECMO [43]. Unique configurations of the VV EMCO for congenital heart disease allow a bicaval dual lumen catheter to be placed under echocardiographic guidance at the atrial septal defect level allowing oxygenated blood to be shunted to the left atrium, and allowing for an oxygenated right to left shunt.

Overall, there has been significant progress in use of the mechanical support as a bridge to lung transplant with >80 % successful bridging and outcomes post lung transplant [36] making this now a viable option for a select number of patients already listed for lung transplant. Attempts at extending this approach to "bridge to recovery," carrying patients over a period of RV pump failure to initiate more aggressive PH therapy have on occasion been successful.

Summary

RV failure arises in a variety of clinical scenarios, ranging from primary RV dysfunction after an acute MI to failure in the setting of endstage severe pulmonary hypertension. Rescue ECLS is a feasible option for bridging PH patients to lung transplant with ECMO or pumpless PA to LA support (Novalung). Options for RVAD mechanical support vary significantly in terms of invasiveness, duration of support, complication profile and durability, and include extracorporeal, paracorporeal, and implantable devices. Efforts at design improvement are now focused on device miniaturization, improved blood compatibility and combination with gas exchange devices for longer periods of time. More recent applications which have not yet been evaluated in larger trials include continuous-flow LVADs used in a biventricular configuration, and low flow devices that combine a blood pump and oxygenator to treat patients with RV failure and pulmonary hypertension. New applications of mechanical devices to provide respiratory support, overcome hemodynamic instability and acute on chronic right ventricular failure, and devices which provide chronic right ventricular support and combined cardiopulmonary support will lead to a new era of support for the patient with the failing RV (Fig. 21.5) [44, 45].
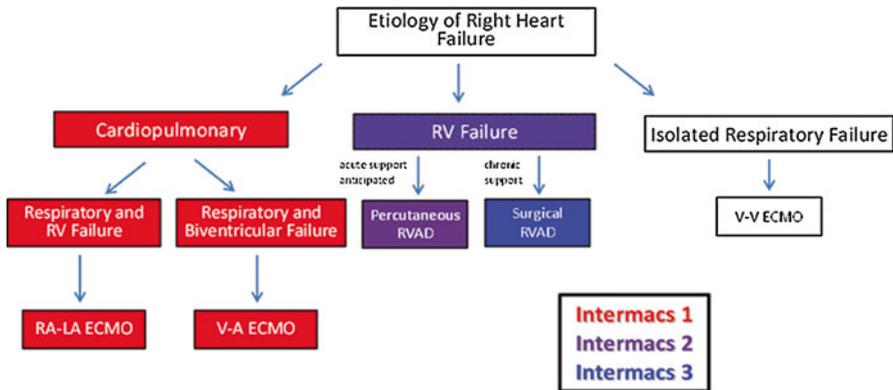
Fig. 21.5 Algorithm for selecting the appropriate RVAD in patients with cardiogenic shock. Image reprinted with permission from Medscape Reference (http://emedicine.medscape.com/) 2013 [44] and Kar et al. [45]

Disclosure Daniel Burkhoff is an employee of Heartware Inc., manufacturer of the Synergy micropump.

References

1. Haddad F, Ashley E, Michelakis ED. New insights for the diagnosis and management of right ventricular failure, from molecular imaging to target right ventricular therapy. Curr Opin Cardiol. 2010;25:131–40.
2. Goldstein JA, Kern MJ. Percutaneous mechanical support for the failing right heart. Cardiol Clin. 2012;30:303–10.
3. Simon MA. Assessment and treatment of right ventricular failure. Nat Rev Cardiol. 2013;10:204–18.
4. Hsu P, Parker J, Egger C, et al. Mechanical circulatory support for right heart failure: current technology and future outlook. J Artif Organs. 2012;36(4):332–47.
5. Haddad F, Skhiri M, Michelakis E. Right ventricular dysfunction in pulmonary hypertension. In: Yuan et al., editors. Textbook of pulmonary vascular disease. New York: Springer; 2011.
6. Price LC, Wort SJ, Finney SJ, Marino PS, Brett SJ. Pulmonary vascular and right ventricular dysfunction in adult critical care: current and emerging options for management: a systematic literature review. Crit Care. 2010;14:R169.
7. Hoeper MM, Granton J. Intensive care unit management of patients with severe pulmonary hypertension and right heart failure. Am J Respir Crit Care Med. 2011;184:1114–24.
8. Fukamachi K, Shiose A, Massiello AL, et al. Implantable continuous-flow right ventricular assist device: lessons learned in development of a Cleveland Clinic device. Ann Thorac Surg. 2012;93(5):1746–52.
9. Hsu P, Parker J, Egger C et al. Mechanical right ventricular assistance—past, present and future. In: World Congress on Medical Physics and Biomedical Engineering, IFMBE Proceedings. 2013; vol 39. p. 1365–8.
10. Fitzpatrick 3rd JR, Frederick JR, Hieseinger W, et al. Early planned institution of biventricular mechanical circulatory support results in improved outcomes compared with delayed conversion of a left ventricular assist device to a biventricular assist device. J Thorac Cardiovasc Surg. 2009;137(4):971–7.

11. Matthews JC, Koelling TM, Pagani FD, et al. The right ventricular failure risk score a preoperative tool for assessing the risk of right ventricular failure in left ventricular assist device candidates. J Am Coll Cardiol. 2008;51(22):2163–72.

12. Kormos RL, Teuteberg JJ, Pagani FD, et al. Right ventricular failure in patients with the HeartMate II continuous-flow left ventricular assist device: incidence, risk factors and effects on outcomes. J Thorac Cardiovasc Surg. 2010;139:1316–24.

13. Gregoric ID, Chandra D, Myers TJ, Scheinin SA, Loyalka P, Kar B. Extracorporeal membrane oxygenation as a bridge to emergency heart-lung transplantation in a patient with idiopathic pulmonary arterial hypertension. J Heart Lung Transplant. 2008;27:466–8.

14. Schmitto JD, Burkhoff D, Avsar M, et al. Two axial-flow synergy micro-pumps as a biventricular assist device in an ovine animal model. J Heart Lung Transplant. 2012;31:1223–9.

15. Gregory SD, Pearcy MJ, Fraser J, et al. Evaluation of inflow cannulation site for implantation of right-sided rotary ventricular assist device. Artif Organs. 2013;37(8):704–11.

16. Bhama JK, Kormos RL, Toyoda Y, et al. Clinical experience using the Levitronix Centrimag system for temporary right ventricular mechanical circulatory support. J Heart Lung Transplant. 2009;29:971–6.

17. Noon GP, Lafuente JA, Irwin S. Acute and temporary ventricular support with BioMedicus centrifugal pump. Ann Thorac Surg. 1999;68:650–4.

18. Morgan JA, Stewart AS, Lee BJ, et al. Role of the Abiomed BVS 5000 device for short-term support and bridge to transplantation. ASAIO J. 2004;50:360–3.

19. Kapur NK, Paruchuri V, Jagannathan A. Mechanical circulatory support for right ventricular failure. JACC: Heart Failure. 2013;1(2):127–34.

20. Cheung A, Leprince P, Freed D. First clinical evaluation of a novel percutaneous right ventricular assist device: Impella RP. J Am Coll Cardiol. 2012;59(13):E872.

21. 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):141–56.

22. Tsukui H, Teuteberg JJ, Murali S, et al. Biventricular assist device utilization for patients with morbid congestive heart failure: a justifiable strategy. Circulation. 2005;112(9 Suppl):I65–72.

23. Drews T, Loebe M, Hennig E, et al. The 'Berlin Heart' assist device. Perfusion. 2000;15:387–96.

24. Slaughter MS, Tsui SS, El-Banayosy A, et al. Results of a multicenter clinical trial with the thoratec implantable ventricular assist device. J Thorac Cardiovasc Surg. 2007;133(6):1573–80.

25. McGee EC, Ahmad U, Tamez D, et al. Biventricular continuous flow VADs demonstrate diurnal flow variation and lead to end-organ recovery. Ann Thorac Surg. 2011;92:e1–3.

26. Loebe M, Bruckner B, Reardon MJ, et al. Initial clinical experience of total cardiac replacement with dual Heartmate II axial flow pumps for severe biventricular heart failure. Methodist Debakey Cardiovasc J. 2011;7:40–4.

27. Punnoose L, Burkhoff D, Rich S, Horn EM. Right ventricular assist device in end-stage pulmonary arterial hypertension: insights from a computational model of the cardiovascular system. Prog Cardiovasc Dis. 2012;55(2):234–43.

28. Rajdev S, Benza R, Misra V. Use of Tandem Heart as a temporary hemodynamic support option for severe pulmonary artery hypertension complicated by cardiogenic shock. J Invasive Cardiol. 2007;19:E226–9.

29. Wang D, Lick SD, Zhou X, et al. Ambulatory oxygenator right ventricular assist device for total right heart and respiratory support. Ann Thorac Surg. 2007;84(5):1699–703.

30. Akay B, Reoma JL, Camboni D, et al. In-parallel artificial lung attachment at high flows in normal and pulmonary hypertension models. Ann Thorac Surg. 2010;90(1):259–65.

31. Camboni D, Philipp A, Arlt M, et al. First experience with a paracorporeal artificial lung in humans. ASAIO J. 2009;55(3):304–6.

32. Schmid C, Philipp A, Hilker M, et al. Bridge to lung transplantation through a pulmonary artery to left atrial oxygenator circuit. Ann Thorac Surg. 2008;85(4):1202–5.

33. De Perrot M, Granton JT, McRae K, et al. Impact of extracorporeal life support on outcome in patients with idiopathic pulmonary arterial hypertension awaiting lung transplantion. J Heart Lung Transplant. 2011;30(9):997–1002.

34. Kirklin JK, Naftel DC, Kormos RL, Stevenson LW, et al. The fourth INTERMACS annual report: 4000 implants and counting. J Heart Lung Transplant. 2012;31:117–26.
35. Olsson KM, Simon A, Strueber M, Hadem J, et al. Extracorporeal membrane oxygenation in nonintubated patients as bridge to lung transplantation. Am J Transplant. 2010;10(9):2173–8.
36. Javidfar J, Brodie D, Iribarne A, et al. Extracorporeal membrane oxygenation as a bridge to lung transplantation and recovery. J Thorac Cardiovasc Surg. 2012;144:716–21.
37. Toyoda Y, Bhama JK, Shigemura N, Zaldonis D, Pilewski J, Crespo M, Bermudez C. Efficacy of extracorporeal membrane oxygenation as a bridge to lung transplantation. J Thorac Cardiovasc Surg. 2013;145(4):1065–70.
38. Shafii AE, Mason DP, Brown CR, Vakil N, Johnston DR, McCurry KR, et al. Growing experience with extracorporeal membrane oxygenation as a bridge to lung transplantation. ASAIO J. 2012;58:526–9.
39. Javidfar J, Brodie D, Wang D, et al. Use of bicaval dual-lumen catheter for adult venovenous extracorporeal membrane oxygenation. Ann Thorac Surg. 2011;91:1763–9.
40. Lynch WR. Artifical lung. In: Annich GM, Lynch WR, MacLaren G, Wilson JM, Bartless RH, editors. ECMO extracorporeal cardiopulmonary support in critical care. 4th ed. Ann Arbor, MI: Extracorporeal Life Support Organization; 2012.
41. Strueber M, Hoeper MM, Fischer S, Cypel M, et al. Bridge to thoracic organ transplantation in patients with pulmonary arterial hypertension using a pumpless lung assist device. Am J Transplant. 2009;9:853–7.
42. Fortenberry J. The history and development of extracorporeal support. In: Annich GM, Lynch WR, MacLaren G, Wilson JM, Bartless RH, editors. ECMO extracorporeal cardiopulmonary support in critical care. 4th ed. Ann Arbor, MI: Extracorporeal Life Support Organization; 2012.
43. Javidfar J, Bacchetta M. Bridge to lung transplantation with extracorporeal membrane oxygenation support. Curr Opin Organ Transplant. 2012;17:496–502.
44. Brittain EL, Maltais S. Extracorporeal tight ventricular assist devices. In: Peter K, editor. Medscape. http://emedicine.medscape.com/article/2052470-overview. Accessed 22 Sept 2013.
45. Kar J, Gregoric ID, Basra SS, et al. The percutaneous ventricular assist device in severe refractory cardiogenic shock. J Am Coll Cardiol. 2011;57(6):688–96.