Mechanical Circulatory Support Devices for Acute Right Ventricular Failure

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ABSTRACT: Right ventricular (RV) failure remains a major cause of global morbidity and mortality for patients with advanced heart failure, pulmonary hypertension, or acute myocardial infarction and after major cardiac surgery. Over the past 2 decades, percutaneously delivered acute mechanical circulatory support pumps specifically designed to support RV failure have been introduced into clinical practice. RV acute mechanical circulatory support now represents an important step in the management of RV failure and provides an opportunity to rapidly stabilize patients with cardiogenic shock involving the RV. As experience with RV devices grows, their role as mechanical therapies for RV failure will depend less on the technical ability to place the device and more on improved algorithms for identifying RV failure, patient monitoring, and weaning protocols for both isolated RV failure and biventricular failure. In this review, we discuss the pathophysiology of acute RV failure and both the mechanism of action and clinical data exploring the utility of existing RV acute mechanical circulatory support devices.

Right ventricular (RV) failure increases short-term mortality.[1–11] This observation has been confirmed in the setting of acute myocardial infarction, cardiogenic shock, advanced left-sided heart failure, and pulmonary hypertension. Four primary mechanisms underlie the development of acute RV failure: contractile failure secondary to myocardial ischemia or inflammation caused by myocarditis, volume overload as a result of right-sided valvular insufficiency, volume overload caused by increased venous return or displacement of the interventricular septum toward the left ventricle (LV) after placement of an LV assist device (LVAD),[12–15] and pressure overload resulting from decompensated left-sided heart failure, worsening pulmonary hypertension, or acute pulmonary embolus. Despite growing awareness of the importance of acute RV failure, mechanical circulatory support (MCS) devices remain the only therapy that specifically targets RV failure. In this review, we discuss the pathophysiology of acute RV failure and both the mechanism of action and clinical data exploring the utility of existing RV acute MCS (AMCS) devices.

PATHOPHYSIOLOGY OF ACUTE RV FAILURE

The majority of RV stroke work maintains forward momentum of blood flow into a highly compliant, low-resistance pulmonic circulation. For this reason, the RV is characterized by low peak systolic pressure and the absence of isovolumic phases of contraction and relaxation during systole and diastole, and it generates one

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sixth the stroke work compared with the LV.[16–18] When RV contractile function is severely impaired, as in the case of RV infarction, the RV manifests reduced peak systolic pressure, increased end-diastolic volume, and reduced stroke volume. Afterload is another major determinant of RV function.[18–25] On a cellular basis, afterload is quantified by changing ventricular wall stress throughout systole. In diseased states such as heart failure, pulmonary hypertension, or acute pulmonary embolism, a rise in RV afterload increases RV pressures and volumes and reduces RV stroke volume.

Determinants of RV afterload include pulmonary vascular resistance, compliance, and, more generally, pulmonary impedance. Impedance results when antegrade flow through the pulmonary artery (PA) generates a backward wave reflection driven by the multiple branch points throughout the pulmonary vasculature. This backward flow wave collides with the antegrade wave, which increases pulmonary pressure and reduces pulmonary blood flow. These wave reflections constitute what is known as pulsatile load.[22,23] PA and pulmonary venous hypertension can increase the magnitude of the pulsatile load, thereby increasing afterload on the RV. In the acute setting, increased pulsatile load decreases RV stroke volume. Recent studies have identified that increased LV filling pressures (also reflected as increases in pulmonary capillary pressure) also reduce PA compliance, increase PA resistance, and increase PA impedance, thereby further increasing RV afterload.[22–25] Thus, LV filling pressure is a major determinant of all 3 components of RV afterload. For this reason, LV failure is a common cause of RV failure.

RV FAILURE: A HEMODYNAMIC PROBLEM

Acute RV failure is a hydraulic problem caused by impaired function of the pump, the valves, or the conduits. Diagnosing acute RV failure remains a major clinical challenge. Physical examination, echocardiographic, and laboratory findings associated with RV failure have been reviewed previously.[4,26–29] Invasive hemodynamic measures can be obtained with a PA catheter and are predictive of RV failure (Table 1). The simplest approach to quantify RV dysfunction is to measure the ratio of right atrial (RA) to pulmonary capillary wedge pressures. In the setting of acute myocardial infarction, Lopez-Sendon and colleagues[30] identified that a ratio of RA pressure to pulmonary capillary wedge pressure >0.86 was associated with pathological evidence of RV infarction at necropsy. Several subsequent studies have demonstrated the utility of the ratio of RA pressure to pulmonary capillary wedge pressure as an index of biventricular congestion and the relative contribution of LV or RV failure among patients with acute myocardial infarction and advanced heart failure and as a predictor of RV failure after LVAD implantation.[13,30,38,39] RV stroke work is another important measure of RV function; however, calculation of RV stroke work requires a true estimate of cardiac output, which is commonly measured with the Fick method in RV failure. The method of thermodilution may underestimate cardiac output as a result of tricuspid regurgitation.[38,40]

Table 1. Hemodynamic Formulas to Assess Right Ventricular Function

Hemodynamic Formulas to Assess RV Function		
Cardiac filling pressures	RAP/PCWP	>0.63 (RVF after LVAD)[13] >0.86 (RVF in acute MI)[30]
PA pulsatility index (PAPi)	(PASP–PADP)/RAP	<1.85 (RVF after LVAD)[31] <1.0 (RVF in acute MI)[32]
Pulmonary vascular resistance	mPAP–PCWP/CO	>3.6 (RVF after LVAD)[15]
Transpulmonary gradient	mPAP–PCWP	Undetermined[33]
Diastolic pulmonary gradient	PADP–PCWP	Undetermined[33,34]
RV stroke work	(mPAP–RAP)× SV×0.0136	<15 (RVF after LVAD)[15] <10 (RVF after acute MI)[35]
RV stroke work index	(mPAP–RAP)/SV index	<0.3–0.6 (RVF after LVAD)[13,31]
PA compliance	SV/(PASP–PADP)	<2.5 (RVF in chronic heart failure)[36]
PA elastance	PASP/SV	Undetermined[37]

CO indicates cardiac output; LVAD, left ventricular assist device; MI, myocardial infarction; mPAP, mean pulmonary artery pressure; PA, pulmonary artery; PADP, pulmonary artery diastolic pressure; PASP, pulmonary artery systolic pressure; PCWP, pulmonary capillary wedge pressure; RAP, right atrial pressure; RV, right ventricular; RVF, right ventricular failure; and SV, stroke volume.

Multiple formulas to assess pulmonary hemodynamics have been developed to quantify RV afterload, including pulmonary vascular resistance, transpulmonary gradient, diastolic pulmonary gradient, PA elastance, PA compliance, and PA impedance.[15,33,34,36,37,41] However, none of these formulas in isolation definitively identifies RV failure. In 2012, we first reported the clinical utility of the PA pulsatility index (PAPi) as a measure of RV failure in the setting of acute MI.[32] The PAPi is the ratio of PA pulse pressure divided by RA pressure. PA pulse pressure provides an estimate of RV pulsatile load and contractile strength. By normalizing PA pulse pressure to RA pressure, the PAPi incorporates RV congestion as another indicator of RV failure. In this first study, we identified that a PAPi <1.0 was a highly sensitive indicator of RV failure in the setting of an acute myocardial infarction. Next, we explored the utility of the PAPi as a marker of RV failure after implantation of a continuous-flow LVAD. In this study, we identified that a PAPi <1.85 was a sensitive predictor of RV failure after LVAD implantation.[31] Several studies have since confirmed the utility of the PAPi as a marker of

RV failure in various settings.[42] The PAPi has not been studied in the setting of PA hypertension but may be of limited value in this setting because of compensatory RV remodeling that allows relatively high PA pulse pressures despite worsening RV function. Further studies exploring the clinical utility of the PAPi as a marker of RV failure are required.

MEDICAL MANAGEMENT OF RV FAILURE

Medical management of acute RV failure has been extensively reviewed previously and begins with treatment of any reversible cause, which commonly includes coronary revascularization for an acute coronary syndrome or thrombolytic therapy for a pulmonary embolism.[4,18] Medical therapy can be divided into 3 major interventions. First, optimization of RV preload with either diuretic therapy or volume expansion is required to maintain cardiac output without worsening venous congestion. For this reason, invasive hemodynamic monitoring with a PA catheter may be useful for patients with RV failure and cardiogenic shock. Second, reducing RV afterload with pulmonary vasodilators may improve RV cardiac output.[43–45] Third, for patients with persistent hemodynamic instability despite optimization of RV loading conditions, inotropic therapy with either a phosphodiesterase inhibitor or β1-adrenergic receptor agonist may further improve total cardiac output.[46] For acute RV failure that is refractory to medical therapy, invasive therapeutic options include atrial septostomy, atrial pacing in the setting of bradycardia, durable MCS, and AMCS devices.

MCS FOR RV FAILURE

Historically, surgically implanted pumps to support RV failure were pulsatile with valves located within the inflow and outflow cannulas. One of the earliest acute RV support devices was a PA balloon counterpulsation pump, which was limited by the need for surgical implantation and variable effects on RV afterload.[47,48] In the early 1990s, rotary-flow RV assist devices (RVADs) demonstrated hemodynamic superiority and better clinical outcomes compared with PA balloon counterpulsation pump for acute RV failure.[49] Second- and third-generation surgical pumps used as RVADs now include roto-dynamic pumps that transfer rotational kinetic energy to the circulation.

Preload and afterload are major determinants of flow through all rotary-flow MCS devices.[50] Device flow (Q) is directly related to rotations per minute of the impeller and indirectly related to pressure gradient between the inlet (preload) and outlet (afterload) of the impeller. This pressure gradient (ie, afterload–preload), referred to as the pressure head (H), varies during the cardiac cycle (Figure 1). For LVADs that draw blood from the LV and pump it to the aorta, H is lowest during ventricular systole when LV pressure is greatest; conversely, H is highest during ventricular diastole when LV pressure is at its lowest value. Accordingly, because flow is inversely related to H, LVAD pump flow is maximum during systole and minimum during diastole. These dynamics are readily appreciated from the rotations per minute–dependent H-Q curve of a pump. For RV support devices that draw blood from the RA and pump to the PA, the dynamics are fundamentally the same, but because variations in RA and PA pressures are not as great as in the LV, variations in RVAD flow are generally significantly less than for LVADs.[51]

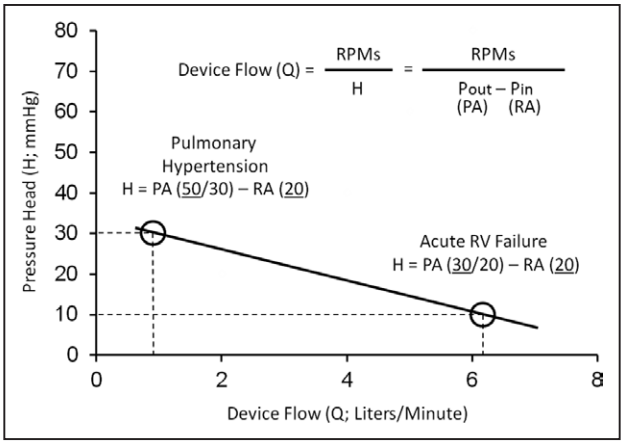

Figure 1. The H-Q curve: a fundamental principle of continuous-flow pumps for right ventricular (RV) support. Primary determinants of device flow (Q) for rotary pumps include rotations per minute (RPM) and the pressure gradient between the inlet and outlet of the impeller referred to as the pressure head (H). In the case of RV acute mechanical circulatory support devices, H is determined by pulmonary artery (PA) pressure (Pout) and right atrial (RA) pressure (Pin). In the setting of pulmonary hypertension, H may be high, which reduces device flow. In the setting of acute severe RV failure, H may be low, which increases device flow.

In the case of RV failure, most MCS systems will include cannulation of the RA and PA to deliver flow into and out of a continuous-flow pump, respectively. H in this case is determined by RA pressure (preload) and PA pressure (afterload). For patients with severe RV failure resulting from acute ischemia or impaired contractility, the difference between RA and PA pressure is often small, and therefore, for fixed rotations per minute, device flow will be high. For patients with RV failure caused by severe pulmonary hypertension, the difference between RA and PA pressure may be large, and for the same rotations per minute setting, device flow will be low.

DURABLE MCS OPTIONS FOR RV FAILURE

In the contemporary era, surgical RVADs continue to use extracorporeal centrifugal-flow pumps such as the CentriMag pump (St. Jude, Minneapolis, MN) and RA-to-PA cannulation with either a thoracotomy or an open sternotomy. Given that large-bore, short cannulas may be used for surgical cannulation, flows achieved with this approach can range up to 6 to 8 L/min. For more durable, long-term support, isolated pulsatile RVADs, surgically deployed rotary-flow RVADs, and biventricular support with pulsatile VADs or total artificial heart replacement are potential options; however, the majority of these patients are required to remain in the hospital under close surveillance. For this reason, surgeons have begun to use commercially available LVADs, including the Jarvik and HeartWare devices, in the RV position to support isolated RV or biventricular failure.[51–56] A major limitation of this approach is that the operating H-Q curve for a surgical LVAD is better suited for the systemic circulation with higher pressure and resistance. Furthermore, because the RV tends to operate in a lower-pressure, less resistant, and more compliant system, surgical LVADs connected to the RA and PA may be more prone to suction events. To overcome this limitation, operators have placed gap spacers to reduce protrusion of the LVAD inlet cannula into the RV and restricted the outflow graft of an LVAD by up to 50%, thereby increasing resistance to VAD outflow to a level that approximates the systemic circulation.[51–56]

Several surgically implanted devices for more durable RV support are emerging. The HeartWare MVAD is an axial-flow pump that has a unique outflow port that originates at a 90° angle from the impeller, thereby functioning in part like a centrifugal-flow pump. The miniature size of the MVAD makes it potentially suitable for RV and biventricular support, which has been tested in preclinical models.[57] The MVAD is not approved for clinical use in the United States. The Circulite Synergy device is another miniaturized hybrid axial-centrifugal–flow pump that has been evaluated in preclinical models for RV and biventricular support.[58–61]

AMCS (PERCUTANEOUS) OPTIONS FOR RV FAILURE

Percutaneously delivered AMCS devices for RV failure (RV-AMCS) are relatively new and provide the opportunity for early intervention in RV failure without the need for surgery. RV-AMCS device options include venoarterial extracorporeal membrane oxygenation (VA-ECMO), the TandemHeart centrifugal-flow pump (TandemLife, Pittsburgh, PA), and the axial-flow Impella RP catheter (Abiomed Inc, Danvers, MA). These devices can be categorized according to their mechanism of action as either direct RV bypass or indirect RV bypass systems (Figure 2). The Impella RP and the TandemHeart RVAD (TH-RVAD) displace blood from the RA to PA, thereby directly bypassing the RV. In contrast, VA-ECMO displaces and oxygenates blood from the RA to the femoral artery, thereby indirectly bypassing the RV. As a result, these systems have distinct hemodynamic effects, depending on whether the patient has isolated RV failure or biventricular failure (Table 2).

For patients with isolated RV failure, activation of either an Impella RP or a TH-RVAD will directly reduce RA pressure, increase mean PA pressure, and increase LV preload. In the presence of preserved LV function, native cardiac output will increase and LV filling pressures will increase or remain unchanged. LV afterload will remain unchanged. In contrast, VA-ECMO will decrease RA and PA pressure initially and decrease LV preload. LV afterload will increase greatly, and therefore, in the presence of preserved LV function, native cardiac output may remain unchanged or decrease.

For patients with biventricular failure, activation of either an Impella RP or a TH-RVAD will directly reduce RA pressure, increase mean PA pressure, and increase LV preload. In the absence of preserved LV function and without an additional LV support device, native cardiac output will remain unchanged or increase slightly. However, cardiac filling pressures could increase significantly, leading to pulmonary edema. LV afterload would increase. In contrast, VA-ECMO will decrease RA pressure and initially decrease PA pressure and LV preload. However, with poor LV function, increased LV afterload will reduce native cardiac out-

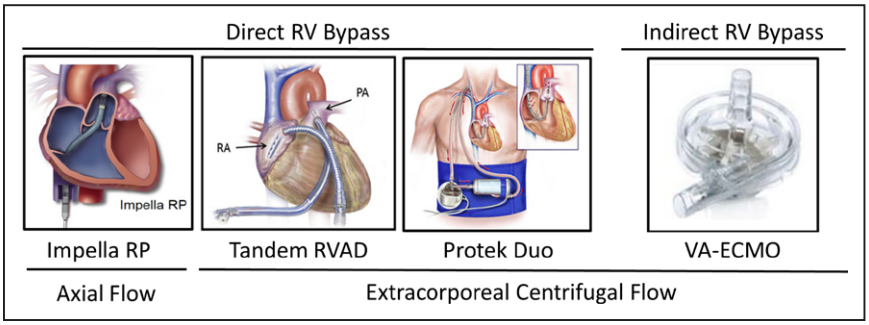

Figure 2. Classifications of acute mechanical circulatory support devices for right ventricular (RV) failure.
Devices options include direct and indirect RV bypass, as well as intracorporeal (Impella RP) and extracorporeal (Tandem RV assist device [RVAD], Protek Duo, venoarterial extracorporeal membrane oxygenation [VA-ECMO]) options.

Table 2. Hemodynamic Effects of Acute Right Ventricular Mechanical Circulatory Support Systems for Isolated Right Ventricular Failure or Biventricular Failure

RV-AMCS Device	Device Characteristics			Hemodynamic Effects				
	Inflow	Outflow	Flow Range, L/min	RAP, mm Hg	Mean PAP, mm Hg	PCWP or LVEDP, mm Hg	LV Afterload (MAP)	Native CO
Isolated RV failure								
Impella RP	RA	PA	2–4	↓	↑	↑	Δ	↑
TH-RVAD or Protek	RA	PA	2–4	↓	↑	↑	Δ	↑
VA-ECMO	RA	FA	2–6	↓	Δ↓	↓	↑↑	Δ↓
Biventricular failure								
Impella RP	RA	PA	2–4	↓	↑	↑↑	↑	Δ↑
TH-RVAD or Protek	RA	PA	2–4	↓	↑	↑↑	↑	Δ↑
VA-ECMO	RA	FA	2–6	↓	↑	↑↑	↑↑	Δ↓
Biventricular support devices (ie, Impella CP+RP)	RA	PA	2–4	↓	↑	Δ↓	Δ↑	↓↓
	LV	AO						

AMCS indicates acute mechanical circulatory support; AO, aorta; CO, cardiac output; FA, femoral artery; LV, left ventricle; LVEDP, left ventricular end-diastolic pressure; MAP, mean arterial pressure; PA, pulmonary artery; PAP, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; RA, right atrial; RAP, right atrial pressure; RV, right ventricular; TH-RVAD, TandemHeart right ventricular assist device; VA-ECMO, venoarterial extracorporeal membrane oxygenation; Δ, no change; ↑ or ↓, mild to moderate change; ↑↑ or ↓↓, moderate to significant change; Δ↑, no change or mild increase; and Δ↓, no change or mild decrease.

put and increase LV filling pressures, thereby leading to pulmonary edema and a subsequent increase in mean PA pressure.

If biventricular mechanical support is initiated for biventricular failure, right-sided support will reduce RA pressure and increase PA pressure, thereby providing preload to the LV. With a concomitant left-sided support device in place, native cardiac output will decrease, and as a result, LV filling pressures will decrease or remain unchanged. Similarly, LV afterload will increase or remain unchanged. Because of these effects, identifying biventricular failure is important when considering RV-AMCS.

Intra-Aortic Balloon Pump

Intra-aortic counterpulsation balloon pumps (IABPs) are commonly used to support RV failure but are not optimally suited for this purpose. IABPs inflate during diastole, which causes increased retrograde flow into the aortic root and increases mean arterial pressure, thus potentially increasing coronary perfusion. During systole, the IABP deflates and produces a pressure sink, which then becomes filled by ejected blood from the LV. As a result, IABP therapy reduces LV afterload and increases mean arterial pressure. IABP therapy does not directly support RV function and theoretically may do so only by reducing LV filling pressures, thereby reducing RV afterload, which in isolation may not significantly improve cardiac function for medically refractory acute RV failure. Clinical data evaluating the use of IABPs in RV failure are limited. Several recent studies have reported limited efficacy of IABP therapy in patients with RV failure.[62,63] In these studies, IABPs failed to augment cardiac output in patients with advanced heart failure who had either reduced RV cardiac power output or echocardiographic and hemodynamic signs of RV failure. For these, reasons, IABPs are not considered primary RV-AMCS devices.

Impella RP: A Direct RV Bypass System

The most recent introduction to the field of RV-AMCS devices is the Impella RP (Abiomed Inc) microaxial-flow catheter. The Impella RP uses a 22F impeller mounted onto an 11F catheter and delivers blood from the RA into the PA (Figures 3 and 4A). The device is delivered via a 23F venous peel-away sheath into the PA with a 0.018-in wire used as a monorail system and requires 1 venous access site (most commonly the right femoral vein). Once in position, the 23F sheath is replaced with a staged 11F to 23F repositioning sheath. After removal, the venous access site is closed with manual compression and a purse-string or deep mattress suture. The Impella RP cannot be used to oxygenate blood.

Since 2013, several reports have described successful use of the Impella RP, initially outside the United States, for RV failure in the setting of cardiac surgery and after LVAD placement[64] (Table 3). In 2015, the RECOVER RIGHT trial prospectively studied the utility of the Impella RP device for medically refractory RV failure in 12 patients with acute myocardial infarction and 18 patients after cardiac surgery.[65] Immediately after Impella RP activation, central venous pressure and cardiac index improved, allowing weaning of inotrope and vasopressor support. The most common adverse events were bleeding and hemolysis. No thromboembolic events were observed, and worsened tricuspid or pulmonary valve dysfunction was infrequent. The primary

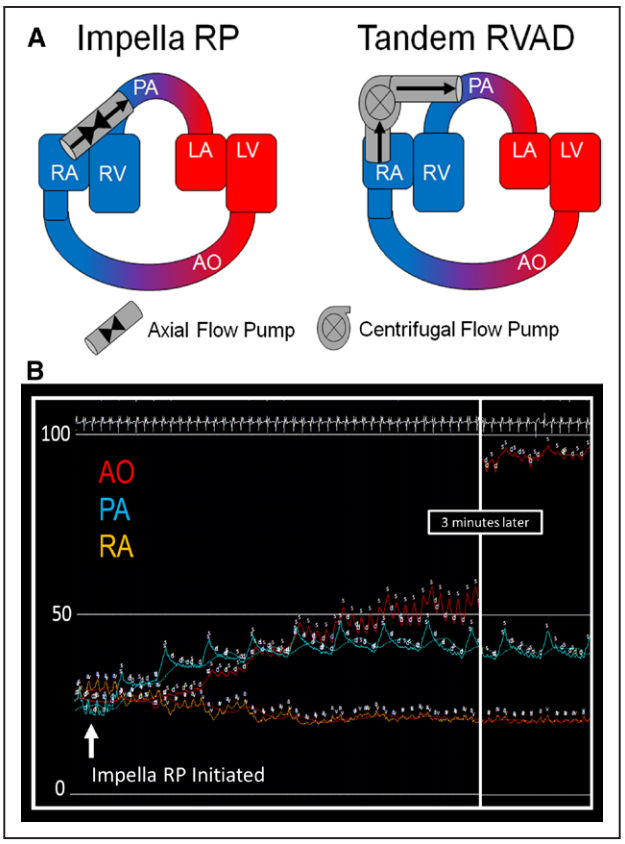

Figure 3. Direct right ventricular (RV) bypass systems. **A**, Both the Impella RP and TandemHeart RV assist device (RVAD) displace blood from the right atrium (RA) to the pulmonary artery (PA), thereby directly bypassing the RV. **B**, Hemodynamic tracings from a patient with RV failure and cardiogenic shock immediately after activation of an Impella RP showing increased aortic (Ao), decreased RA, and increased PA pressures. LA indicates left atrium; and LV, left ventricle.

end point of survival to 30 days or hospital discharge of 73% compares favorably to a prior prospective study of a surgical RVAD in a similar patient population.[66] The Impella RP has been used to support patients with RV failure associated with malignant ventricular arrhythmias and severe mitral regurgitation.[67–69]

The TH-RVAD and Protek Duo Cannula: Direct RV Bypass Systems

The TH-RVAD uses an extracorporeal centrifugal-flow pump and 2 venous cannulas to deliver blood from the RA to the main PA. One 21F inflow cannula is placed in the RA, and a second 21F outflow cannula is inserted into the main PA. Most TH-RVAD cannulas are deployed via both femoral veins. For bilateral femoral cannulation, the outflow cannula is placed in the main PA via the right femoral vein, and the inflow cannula is placed in the RA via the left femoral vein. In patients with long torsos (distance from the femoral vein to the fifth intercostal space exceeds 58 cm), the outflow cannula can be placed in the main PA via the right internal jugular vein. This approach can also be used if limitations to femoral venous access exist, including infection, thrombosis, or inferior vena caval filters.[70] When right internal jugular access is used, the outflow cannula is situated into the main PA via the right internal jugular, and the RA inflow cannula is positioned via a femoral vein (Figure 3). Use of the right internal jugular led to development of the Protek Duo dual-lumen cannula, which contains 2 lumens within one 29F or 31F cannula (Figure 2).[71,72] One lumen serves as an inflow cannula

Table 3. Clinical Studies Evaluating the Utility of Acute Mechanical Circulatory Support Systems for Right Ventricular Failure

Device	Patient Population	Outcomes	Study
Impella RP	18 Patients (15 Impella RD, 3 Impella RP) AMI, 39% (n=7) PCCS, 22% (n=4) Post-OHT, 17% (n=3) Post-LVAD, 11% (n=2) Myocarditis, 11% (n=2)	30-d Survival, 72% 1-y Survival, 50% Hemodynamic effects: increased CI, decreased RA pressure	Cheung et al[83]
	30 Patients Post-LVAD (n=18) PCCS/AMI (n=12)	30-d Survival, 73.3% Hemodynamic effects: increased CI, decreased RA pressure	Anderson et al[65]
TH-RVAD	46 Patients Postvalve surgery, 32% (n=15) AMI, 25% (n=12) Post-OHT, 11% (n=5) Post-LVAD, 11% (n=5) Post-CABG, 7% (n=3) Chronic HF, 7% (n=3) Myocarditis, 7% (n=3)	In-hospital mortality, 57% Hemodynamic effects: increased MAP, CI, and PA O_2 saturation; decreased RA and PA systolic pressures No change in number of vasopressors/inotropes	Kapur et al[84]
	9 Patients Sepsis, 11.1% (n=1) PCCS, 22.2% (n=2) IWMI, 66.7% (n=6)	In-hospital mortality 44% Hemodynamic effects: increased MAP, CI, RV stroke work; decreased RA pressure	Kapur et al[82]
VA-ECMO	179 Patients PCCS, 39% (n=70) AMI, 26% (n=46) Primary graft failure, 10% (n=17) ADHF, 13% (n=24)	In-hospital mortality, 38.6% (n=69) Hemodynamic effects: decreased RA pressure and mean PA pressure	Truby et al[85]

ADHF indicates acute decompensated heart failure; AMI, acute myocardial infarction; CABG, coronary artery bypass graft; CI, cardiac index; HF, heart failure; IWMI, inferior wall myocardial infarction; LVAD, left ventricular assist device; MAP, mean arterial pressure; OHT, orthotopic heart transplantation; PA, pulmonary artery; PCCS, postcardiotomy cardiogenic shock; RA, right atrial; RV, right ventricular; TH-RVAD, TandemHeart right ventricular assist device; and VA-ECMO, venoarterial extracorporeal membrane oxygenation.

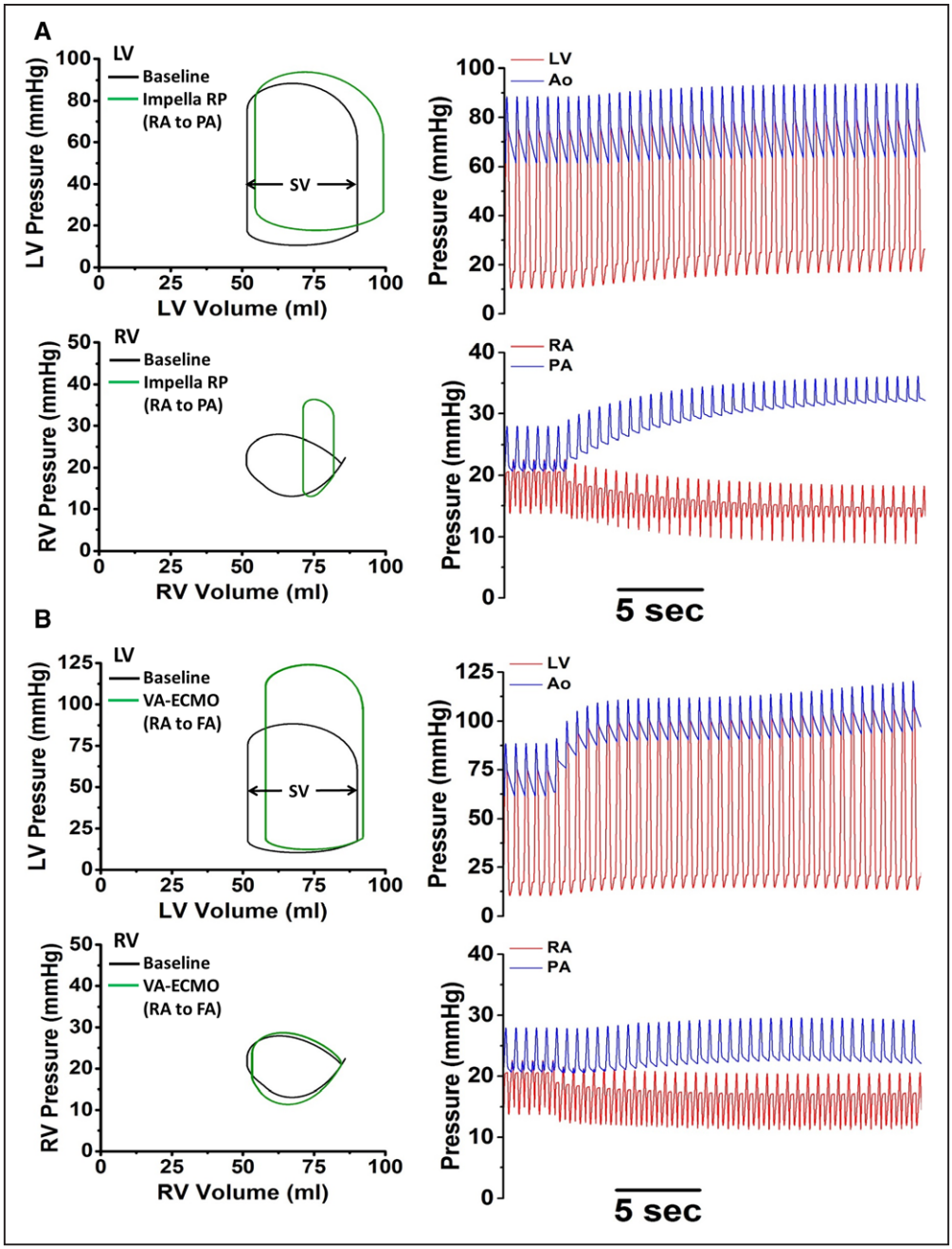

Figure 4. Biventricular hemodynamics after right ventricular (RV) bypass.
Simulated left ventricular (LV) and RV pressure-volume loops and hemodynamic tracings of LV, aortic (Ao), right atrial (RA), and pulmonary artery (PA) pressures. **A**, Activation of a direct RV bypass system (ie, Impella RP or TandemHeart RV assist device) reduces native RV stroke volume (SV), increases RV and PA peak systolic pressure, narrows PA pulse pressure, and decreases RA pressure. When preload to the LV is increased, LV diastolic pressure and LV SV increase. SV is depicted for the baseline LV loops. **B**, Activation of an indirect RV bypass system (ie, venoarterial [VA-ECMO] or veno-veno-arterial extracorporeal membrane oxygenation) reduces RA pressure with no effect on PA peak systolic pressure, PA pulse pressure, or native RV SV. When afterload to the LV is increased, LV systolic pressure increases and native LV SV decreases. FA indicates femoral artery.

and encompasses a series of inflow vents positioned across the superior vena cava into the RA. The second lumen has a multifenestrated distal tip to deliver blood into the main PA. The inflow cannula drains blood from the RA into an extracorporeal centrifugal pump, which delivers blood back to the PA.

Any centrifugal pump with cannulas positioned in the RA and PA can be used to provide both RV support and improved systemic oxygenation by splicing an oxygenator into the circuit. This configuration is referred to as an oxy-RVAD.[73,74] In contrast, veno-veno ECMO does not provide RV support because blood is drained from

the superior or inferior vena cava and delivered back to the RA. Direct RV bypass requires positioning of the outflow cannula in the PA.

Use of the TH-RVAD has been reported in multiple scenarios, including acute myocardial infarction,[75–77] post-LVAD implantation,[78] severe pulmonary hypertension,[79] severe acute mitral regurgitation,[80] and cardiac rejection after orthotopic heart transplantation.[81] Several case reports have recently described use of the Protek Duo cannula for RV failure in the setting of LVAD implantation and cardiogenic shock resulting from decompensated severe pulmonary hypertension.[71,72] In 2011, a single-center experience reported improvements in mean arterial pressure, RA pressure, cardiac index, RV stroke work, and mixed venous oxygen saturation in 9 patients within 24 hours of TH-RVAD implantation for various causes[82] (Table 3). The in-hospital mortality rate was 44% and highest among patients with delayed TH-RVAD placement. In this report, no mechanical complications were observed during or after device implantation. In 2014, the THRIVE study (TandemHeart in Right Ventricular Support) retrospectively studied 46 patients receiving a TH-RVAD in 8 tertiary referral centers.[84] The TH-RVAD was associated with acute hemodynamic improvement. In-hospital mortality was 57%, with the lowest mortality in patients with RV failure secondary to acute myocardial infarction or post-LVAD implantation. Increased age, biventricular failure, and TIMI (Thrombolysis in Myocardial Infarction) major bleeding were more prevalent in patients who did not survive to hospital discharge.

VA-ECMO: An Indirect RV Bypass System

VA-ECMO is frequently implanted during cardiopulmonary collapse or biventricular failure to improve systemic oxygenation. VA-ECMO can be deployed percutaneously via an extracorporeal centrifugal pump (ie, TandemHeart, CentriMag, Rotaflow, or Biomedicus pumps) and displaces venous blood from the RA across an oxygenator and into the arterial circulation.[86,87] In select cases, 2 venous inflow cannulas can be placed in the RA and PA, thereby draining the RV from 2 locations. This configuration is known as veno-veno-arterial ECMO. In the setting of acute RV failure, VA-ECMO or veno-veno-arterial ECMO reduces RV preload and RV cardiac output. However, by displacing blood from the venous to the arterial system, VA-ECMO or veno-veno-arterial ECMO increases systemic mean arterial pressure and LV afterload (Figures 4B and 5). If LV function is impaired, this rise in LV afterload may increase LA and PA pressures, thereby causing progressive acute lung injury and worse clinical outcomes.[86–88] For this reason, if LV function is impaired, VA-ECMO often requires a second device to decompress the LV such as an IABP, Impella LV device, or a cannula placed in the LA or LV.[89–92]

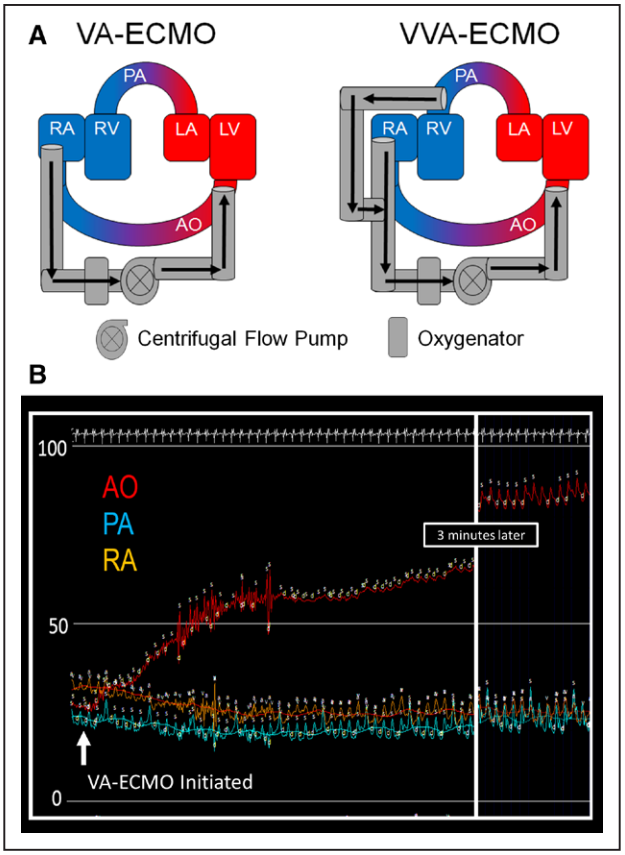

Figure 5. Indirect right ventricular (RV) bypass systems. Both (**A**) veno-arterial (VA-ECMO) and veno-veno-arterial (VVA-ECMO) extracorporeal membrane oxygenation reduces RV preload by draining blood from the right atrium (RA) or both the RA and pulmonary artery (PA), respectively. Both systems oxygenate and transfer blood to the aorta (Ao). **B**, Hemodynamic tracings from a patient with RV failure and cardiogenic shock immediately after activation of VA-ECMO showing increased Ao and decreased RA pressures. PA pressure may decrease or stay the same. LA indicates left atrium; and LV, left ventricle.

Clinical data supporting the use of VA-ECMO in the setting of acute RV failure are limited to case reports and small case series,[93–95] but the effect of VA-ECMO on right-sided heart hemodynamics remains largely undefined (Table 3). In a study of 179 patients with refractory cardiogenic shock most commonly resulting from acute myocardial infarction or postcardiotomy shock, mean central venous pressure decreased by 5 mm Hg and mean PA pressure decreased by 11 mm Hg after 24 hours of ECMO support.[85] These results imply that VA-ECMO may have salutary hemodynamic effects in patients with RV failure. Further studies exploring the effect of VA-ECMO on RV function and the potential utility of VA-ECMO as a management option for RV failure are needed.

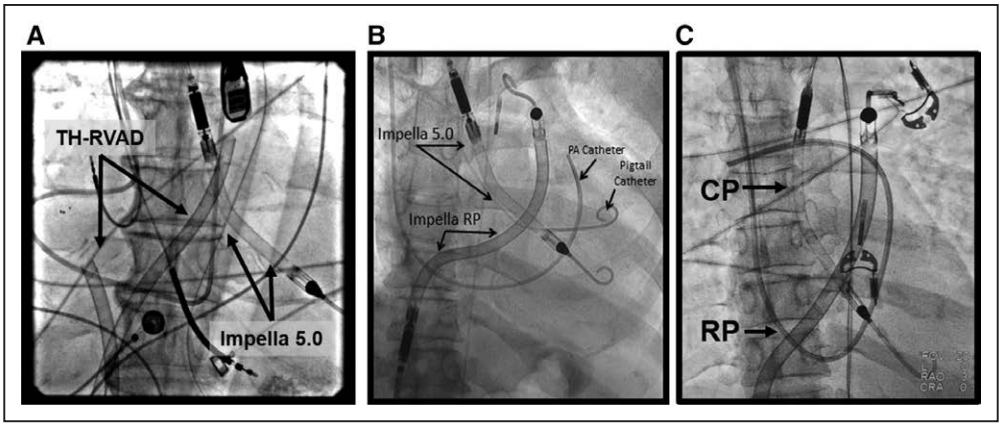

Figure 6. Percutaneous biventricular acute mechanical circulatory support device configurations. Radiographic images of 3 different biventricular support configurations are shown: (**A**) combined TandemHeart right ventricular assist device (TH-RVAD) and an Impella 5.0 left ventricular (LV) support device, (**B**) combined Impella RP and Impella 5.0 LV support devices, and (**C**) combined Impella CP and RP support devices. **Black arrows** identify cannulas for each device.

Acute Biventricular Circulatory Support

With the advent of RV-AMCS devices, mechanical support options for cardiogenic shock caused by biventricular failure have evolved beyond surgically implanted biventricular pumps to now include various combinations of percutaneously delivered centrifugal- and axial-flow pumps. Biventricular support can be achieved with 2 TandemHeart devices, which require 4 separate 21F cannulas: 2 for LV support and 2 for RV support. Several reports have described the use of an IABP plus TH-RVAD,[96] Impella 2.5 plus TH-RVAD,[97] Impella 5.0 plus TH-RVAD,[98] Impella 5.0 plus Impella RP,[99] and Impella CP plus RP[100] for biventricular support (Figure 6). As awareness of concomitant RV involvement in cardiogenic shock grows, the use of biventricular support strategies to improve clinical outcomes will require further study.

Patient Selection and Management of RV-Specific AMCS Devices

Given the recent introduction of RV-AMCS device options, no specific guidelines to optimize device selection and management exist. On the basis of the existing literature and our clinical experience, we have provided a few key recommendations and a proposed algorithm for the use of RV-AMCS devices (Figure 7). Early diagnosis with the use of hemodynamic, echocardiographic, and laboratory parameters to identify RV failure, to assess LV function, and to rule out pericardial diseases, including causes of constrictive or restrictive physiology, is a critical first step. Next, initial treatment should focus on reversible causes of RV failure such as RV myocardial infarction or pulmonary embolus. If not done already, acquiring hemodynamic data with a PA catheter will confirm the diagnosis of RV failure and provide a real-time assessment of cardiac function and volume status during treatment, which should focus on optimizing cardiac preload, considering inotropic support, and reducing RV afterload by adding pulmonary vasodilators and optimizing mechanical ventilator settings.

For patients whose blood pressure or cardiac index fails to improve despite initial treatment with an inotrope or a vasopressor, early use of RV-AMCS should be considered. Hemodynamic indexes (Table 1) may be helpful when trying to determine whether RV-AMCS is needed. Before RV-AMCS device activation, LV function must be carefully assessed. Operators should also clearly define their "exit strategy" and treatment objectives before AMCS device use, which may include RV support as a bridge to recovery, a bridge to LVAD, biventricular VAD, a total artificial heart, or a bridge to orthotopic heart transplantation. In the setting of RV myocardial infarction, the decision may be fairly straightforward. However, in patients with advanced heart failure, a heart team–based approach should be used to define whether RV-AMCS devices should be used. The need for an oxygenator should be anticipated because that can influence device selection. After the initiation of RV-AMCS, hemodynamic monitoring remains an important component of the management strategy by providing measurements of biventricular filling pressures, PA pulsatility, and Fick-derived cardiac output as indicators of optimal RV-AMCS device function and RV recovery. In the setting of impaired LV function, isolated use of an RV support device can lead to LV volume overload and acute pulmonary injury. Conversely, if isolated LV support is initiated in the setting of biventricular failure, then LV suction may occur as a result of limited preload supplied by the failing RV. In these cases, biventricular support should be considered. As is the case with most support devices, hemodynamic stability and adequate systemic perfusion at a low device setting often indicate that device removal is feasible.

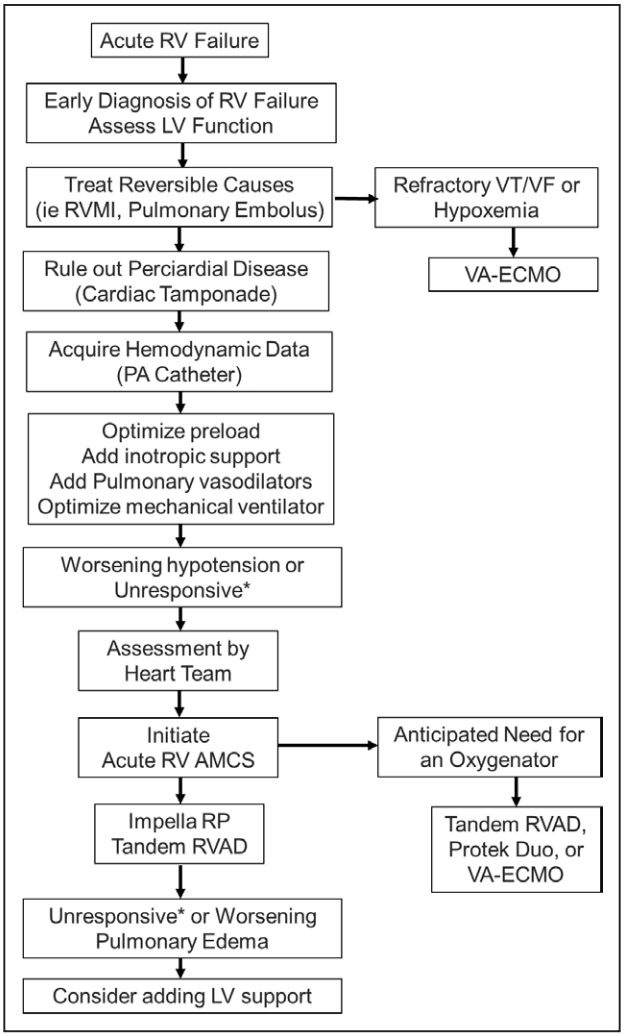

Figure 7. Proposed algorithm for right ventricular (RV) acute mechanical circulatory support (AMCS) device use in RV failure.

LV indicates left ventricular; PA, pulmonary artery; RVAD, right ventricular assist device; RVMI, right ventricular myocardial infarction; VA-ECMO, venoarterial extracorporeal membrane oxygenation; and VT/VF, ventricular tachycardia/ventricular fibrillation. *Unresponsive defined by new or persistent systolic blood pressure <90 mm Hg or cardiac index <2.2 requiring ≥1 inotrope or vasopressor worsening end-organ perfusion.

FUTURE DIRECTIONS

Present-day RV-AMCS devices are restricted by the need for large-bore cannulas inserted via the femoral or internal jugular veins. Mobility for patients requiring RV-AMCS is limited. Future directions for RV-AMCS include the development of ambulatory and potentially fully implantable systems. The Circulite device (HeartWare Inc) is a fully implantable hybrid axial-centrifugal–flow pump that can shuttle blood from the RA to PA. Early testing of the Circulite system for RV failure in the setting of pulmonary hypertension is underway. In addition to engineering advances, the role of RV-AMCS devices as mechanisms to improve hepatic and renal congestion remains largely unexplored. Because multiorgan failure is a major reason for mortality in the setting of RV failure, RV-AMCS devices may serve not only to unload the RV but also to decongest and improve vital organ function.

SUMMARY

RV failure remains a major cause of morbidity and mortality. Percutaneous RV support devices play an important role in the management of RV failure with the ability to rapidly stabilize patients with cardiogenic shock involving the RV. The role of RV-AMCS devices will be as a bridge to therapy or recovery while advancements in coronary intervention, pulmonary hypertension, cardiac surgery, transplantation medicine, and VAD technology offer options for patients who survive cardiogenic shock. As RV devices become more commonly used, their role in the management of RV failure will be less dependent on operator skill and more dependent on improved algorithms for the early detection of RV failure, device selection, patient monitoring, and weaning protocols for both isolated RV failure and biventricular failure.

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FOOTNOTES

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REFERENCES

1. Voelkel NF, Quaife RA, Leinwand LA, Barst RJ, McGoon MD, Meldrum DR, Dupuis J, Long CS, Rubin LJ, Smart FW, Suzuki YJ, Gladwin M, Denholm EM, Gail DB; National Heart, Lung, and Blood Institute Working Group on Cellular and Molecular Mechanisms of Right Heart Failure. Right ventricular function and failure: report of a National Heart, Lung, and Blood Institute working group on cellular and molecular mechanisms of right heart failure. *Circulation*. 2006;114:1883–1891. doi: 10.1161/CIRCULATIONAHA.106.632208.
2. Mehta SR, Eikelboom JW, Natarajan MK, Diaz R, Yi C, Gibbons RJ, Yusuf S. Impact of right ventricular involvement on mortality and morbidity in

patients with inferior myocardial infarction. *J Am Coll Cardiol*. 2001;37:37–43.
3. Zehender M, Kasper W, Kauder E, Schönthaler M, Geibel A, Olschewski M, Just H. Right ventricular infarction as an independent predictor of prognosis after acute inferior myocardial infarction. *N Engl J Med*. 1993;328:981–988. doi: 10.1056/NEJM199304083281401.
4. Piazza G, Goldhaber SZ. The acutely decompensated right ventricle: pathways for diagnosis and management. *Chest*. 2005;128:1836–1852. doi: 10.1378/chest.128.3.1836.
5. Ghio S, Gavazzi A, Campana C, Inserra C, Klersy C, Sebastiani R, Arbustini E, Recusani F, Tavazzi L. Independent and additive prognostic value of right ventricular systolic function and pulmonary artery pressure in patients with chronic heart failure. *J Am Coll Cardiol*. 2001;37:183–188.
6. Jacobs AK, Leopold JA, Bates E, Mendes LA, Sleeper LA, White H, Davidoff R, Boland J, Modur S, Forman R, Hochman JS. Cardiogenic shock caused by right ventricular infarction: a report from the SHOCK registry. *J Am Coll Cardiol*. 2003;41:1273–1279.
7. Budweiser S, Jörres RA, Riedl T, Heinemann F, Hitzl AP, Windisch W, Pfeifer M. Predictors of survival in COPD patients with chronic hypercapnic respiratory failure receiving noninvasive home ventilation. *Chest*. 2007;131:1650–1658. doi: 10.1378/chest.06-2124.
8. Benza RL, Miller DP, Gomberg-Maitland M, Frantz RP, Foreman AJ, Coffey CS, Frost A, Barst RJ, Badesch DB, Elliott CG, Liou TG, McGoon MD. Predicting survival in pulmonary arterial hypertension: insights from the Registry to Evaluate Early and Long-Term Pulmonary Arterial Hypertension Disease Management (REVEAL). *Circulation*. 2010;122:164–172. doi: 10.1161/CIRCULATIONAHA.109.898122.
9. Haddad F, Peterson T, Fuh E, Kudelko KT, de Jesus Perez V, Skhiri M, Vagelos R, Schnittger I, Denault AY, Rosenthal DN, Doyle RL, Zamanian RT. Characteristics and outcome after hospitalization for acute right heart failure in patients with pulmonary arterial hypertension. *Circ Heart Fail*. 2011;4:692–699. doi: 10.1161/CIRCHEARTFAILURE.110.949933.
10. Apostolakis S, Konstantinides S. The right ventricle in health and disease: insights into physiology, pathophysiology and diagnostic management. *Cardiology*. 2012;121:263–273. doi: 10.1159/000338705.
11. Sanchez O, Planquette B, Roux A, Gosset-Woimant M, Meyer G. Triaging in pulmonary embolism. *Semin Respir Crit Care Med*. 2012;33:156–162. doi: 10.1055/s-0032-1311794.
12. Fukamachi K, McCarthy PM, Smedira NG, Vargo RL, Starling RC, Young JB. Preoperative risk factors for right ventricular failure after implantable left ventricular assist device insertion. *Ann Thorac Surg*. 1999;68:2181–2184.
13. Kormos RL, Teuteberg JJ, Pagani FD, Russell SD, John R, Miller LW, Massey T, Milano CA, Moazami N, Sundareswaran KS, Farrar DJ; 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;139:1316–1324. doi: 10.1016/j.jtcvs.2009.11.020.
14. 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;51:2163–2172. doi: 10.1016/j.jacc.2008.03.009.
15. Drakos SG, Janicki L, Horne BD, Kfoury AG, Reid BB, Clayson S, Horton K, Haddad F, Li DY, Renlund DG, Fisher PW. Risk factors predictive of right ventricular failure after left ventricular assist device implantation. *Am J Cardiol*. 2010;105:1030–1035. doi: 10.1016/j.amjcard.2009.11.026.
16. Sheehan F, Redington A. The right ventricle: anatomy, physiology and clinical imaging. *Heart*. 2008;94:1510–1515. doi: 10.1136/hrt.2007.132779.
17. Greyson CR. Evaluation of right ventricular function. *Curr Cardiol Rep*. 2011;13:194–202. doi: 10.1007/s11886-011-0174-5.
18. Haddad F, Doyle R, Murphy DJ, Hunt SA. Right ventricular function in cardiovascular disease, part II: pathophysiology, clinical importance, and management of right ventricular failure. *Circulation*. 2008;117:1717–1731. doi: 10.1161/CIRCULATIONAHA.107.653584.
19. Pinsky MR. The right ventricle: interaction with the pulmonary circulation. *Crit Care*. 2016;20:266. doi: 10.1186/s13054-016-1440-0.
20. Faber MJ, Dalinghaus M, Lankhuizen IM, Steendijk P, Hop WC, Schoemaker RG, Duncker DJ, Lamers JM, Helbing WA. Right and left ventricular function after chronic pulmonary artery banding in rats assessed with biventricular pressure-volume loops. *Am J Physiol Heart Circ Physiol*. 2006;291:H1580–H1586. doi: 10.1152/ajpheart.00286.2006.
21. Kapur NK, Paruchuri V, Aronovitz MJ, Qiao X, Mackey EE, Daly GH, Ughreja K, Levine J, Blanton R, Hill NS, Karas RH. Biventricular remodeling in murine models of right ventricular pressure overload. *PLoS One*. 2013;8:e70802. doi: 10.1371/journal.pone.0070802.
22. Champion HC, Michelakis ED, Hassoun PM. Comprehensive invasive and noninvasive approach to the right ventricle-pulmonary circulation unit: state of the art and clinical and research implications. *Circulation*. 2009;120:992–1007.
23. Tedford RJ. Determinants of right ventricular afterload (2013 Grover Conference series). *Pulm Circ*. 2014;4:211–219. doi: 10.1086/676020.
24. Pellegrini P, Rossi A, Pasotti M, Raineri C, Cicoira M, Bonapace S, Dini FL, Temporelli PL, Vassanelli C, Vanderpool R, Naeije R, Ghio S. Prognostic relevance of pulmonary arterial compliance in patients with chronic heart failure. *Chest*. 2014;145:1064–1070. doi: 10.1378/chest.13-1510.
25. Rosenkranz S, Gibbs JS, Wachter R, De Marco T, Vonk-Noordegraaf A, Vachiéry JL. Left ventricular heart failure and pulmonary hypertension. *Eur Heart J*. 2016;37:942–954. doi: 10.1093/eurheartj/ehv512.
26. Tadic M. Multimodality evaluation of the right ventricle: an updated review. *Clin Cardiol*. 2015;38:770–776. doi: 10.1002/clc.22443.
27. Ryan JJ, Tedford RJ. Diagnosing and treating the failing right heart. *Curr Opin Cardiol*. 2015;30:292–300. doi: 10.1097/HCO.0000000000000164.
28. Portnoy SG, Rudski LG. Echocardiographic evaluation of the right ventricle: a 2014 perspective. *Curr Cardiol Rep*. 2015;17:21. doi: 10.1007/s11886-015-0578-8.
29. Kubba S, Davila CD, Forfia PR. Methods for evaluating right ventricular function and ventricular-arterial coupling. *Prog Cardiovasc Dis*. 2016;59:42–51. doi: 10.1016/j.pcad.2016.06.001.
30. Lopez-Sendon J, Coma-Canella I, Gamallo C. Sensitivity and specificity of hemodynamic criteria in the diagnosis of acute right ventricular infarction. *Circulation*. 1981;64:515–525.
31. Morine KJ, Kiernan MS, Pham DT, Paruchuri V, Denofrio D, Kapur NK. Pulmonary artery pulsatility index is associated with right ventricular failure after left ventricular assist device surgery. *J Card Fail*. 2016;22:110–116. doi: 10.1016/j.cardfail.2015.10.019.
32. Korabathina R, Heffernan KS, Paruchuri V, Patel AR, Mudd JO, Prutkin JM, Orr NM, Weintraub A, Kimmelstiel CD, Kapur NK. The pulmonary artery pulsatility index identifies severe right ventricular dysfunction in acute inferior myocardial infarction. *Catheter Cardiovasc Interv*. 2012;80:593–600. doi: 10.1002/ccd.23309.
33. Aschauer S, Kammerlander AA, Zotter-Tufaro C, Ristl R, Pfaffenberger S, Bachmann A, Duca F, Marzluf BA, Bonderman D, Mascherbauer J. The right heart in heart failure with preserved ejection fraction: insights from cardiac magnetic resonance imaging and invasive haemodynamics. *Eur J Heart Fail*. 2016;18:71–80. doi: 10.1002/ejhf.418.
34. Handoko ML, De Man FS, Oosterveer FP, Bogaard HJ, Vonk-Noordegraaf A, Westerhof N. A critical appraisal of transpulmonary and diastolic pressure gradients. *Physiol Rep*. 2016;4:e12910.
35. Pouleur H, Lefevre J, van Eyll C, Jaumin PM, Charlier AA. Significance of pulmonary input impedance in right ventricular performance. *Cardiovasc Res*. 1978;12:617–629.
36. Dupont M, Mullens W, Skouri HN, Abrahams Z, Wu Y, Taylor DO, Starling RC, Tang WH. Prognostic role of pulmonary arterial capacitance in advanced heart failure. *Circ Heart Fail*. 2012;5:778–785. doi: 10.1161/CIRCHEARTFAILURE.112.968511.
37. Amin A, Taghavi S, Esmaeilzadeh M, Bakhshandeh H, Naderi N, Maleki M. Pulmonary arterial elastance for estimating right ventricular afterload in systolic heart failure. *Congest Heart Fail*. 2011;17:288–293. doi: 10.1111/j.1751-7133.2011.00222.x.
38. Drazner MH, Velez-Martinez M, Ayers CR, Reimold SC, Thibodeau JT, Mishkin JD, Mammen PP, Markham DW, Patel CB. Relationship of right- to left-sided ventricular filling pressures in advanced heart failure: insights from the ESCAPE trial. *Circ Heart Fail*. 2013;6:264–270. doi: 10.1161/CIRCHEARTFAILURE.112.000204.
39. Cigarroa RG, Lange RA, Williams RH, Bedotto JB, Hillis LD. Underestimation of cardiac output by thermodilution in patients with tricuspid regurgitation. *Am J Med*. 1989;86:417–420.
40. Hamilton MA, Stevenson LW, Woo M, Child JS, Tillisch JH. Effect of tricuspid regurgitation on the reliability of the thermodilution cardiac output technique in congestive heart failure. *Am J Cardiol*. 1989;64:945–948.
41. Vonk Noordegraaf A, Westerhof BE, Westerhof N. The relationship between the right ventricle and its load in pulmonary hypertension. *J Am Coll Cardiol*. 2017;69:236–243. doi: 10.1016/j.jacc.2016.10.047.
42. Kang G, HA R, Banerjee D. Pulmonary artery pulsatility index predicts right ventricular failure after left ventricular assist device implantation. *J Heart Lung Transplant*. 2016;35:67–73.
43. Cockrill BA, Kacmarek RM, Fifer MA, Bigatello LM, Ginns LC, Zapol WM, Semigran MJ. Comparison of the effects of nitric oxide, nitroprusside, and nifedipine on hemodynamics and right ventricular contractility in patients with chronic pulmonary hypertension. *Chest*. 2001;119:128–136.

44. Koelling TM, Kirmse M, Di Salvo TG, Dec GW, Zapol WM, Semigran MJ. Inhaled nitric oxide improves exercise capacity in patients with severe heart failure and right ventricular dysfunction. *Am J Cardiol*. 1998;81:1494–1497.
45. Wasson S, Govindarajan G, Reddy HK, Flaker G. The role of nitric oxide and vasopressin in refractory right heart failure. *J Cardiovasc Pharmacol Ther*. 2004;9:9–11. doi: 10.1177/107424840400900i102.
46. Eichhorn EJ, Konstam MA, Weiland DS, Roberts DJ, Martin TT, Stransky NB, Salem DN. Differential effects of milrinone and dobutamine on right ventricular preload, afterload and systolic performance in congestive heart failure secondary to ischemic or idiopathic dilated cardiomyopathy. *Am J Cardiol*. 1987;60:1329–1333.
47. Patel SM, Allaire PE, Wood HG, Throckmorton AL, Tribble CG, Olsen DB. Methods of failure and reliability assessment for mechanical heart failure. *Artif Organ*. 2005;29:15–25.
48. Flege JB Jr, Wright CB, Reisinger TJ. Successful balloon counterpulsation for right ventricular failure. *Ann Thorac Surg*. 1984;37:167–168.
49. Taylor AJ, Edwards FH, Macon MG, Worley B, Graeber GM. A comparative evaluation of pulmonary artery balloon counterpulsation and a centrifugal flow pump in an experimental model of right ventricular infarction. *J Extra Corpor Technol*. 1990;22:85–90.
50. Moazami N, Fukamachi K, Kobayashi M, Smedira NG, Hoercher KJ, Massiello A, Lee S, Horvath DJ, Starling RC. Axial and centrifugal continuous-flow rotary pumps: a translation from pump mechanics to clinical practice. *J Heart Lung Transplant*. 2013;32:1–11. doi: 10.1016/j.healun.2012.10.001.
51. Karimov JH, Sunagawa G, Horvath D, Fukamachi K, Starling RC, Moazami N. Limitations to chronic right ventricular assist device support. *Ann Thorac Surg*. 2016;102:651–658. doi: 10.1016/j.athoracsur.2016.02.006.
52. Krabatsch T, Hennig E, Stepanenko A, Schweiger M, Kukucka M, Huebler M, Potapov E, Hetzer R. Evaluation of the HeartWare HVAD centrifugal pump for right ventricular assistance in an in vitro model. *ASAIO J*. 2011;57:183–187. doi: 10.1097/MAT.0b013e318211ba2b.
53. Frazier OH, Myers TJ, Gregoric I. Biventricular assistance with the Jarvik FlowMaker: a case report. *J Thorac Cardiovasc Surg*. 2004;128:625–626. doi: 10.1016/j.jtcvs.2004.02.023.
54. Saito S, Sakaguchi T, Miyagawa S, Yoshikawa Y, Yamauchi T, Ueno T, Kuratani T, Sawa Y. Biventricular support using implantable continuous-flow ventricular assist devices. *J Heart Lung Transplant*. 2011;30:475–478. doi: 10.1016/j.healun.2010.11.013.
55. Strueber M, Meyer AL, Malehsa D, Haverich A. Successful use of the HeartWare HVAD rotary blood pump for biventricular support. *J Thorac Cardiovasc Surg*. 2010;140:936–937. doi: 10.1016/j.jtcvs.2010.04.007.
56. Hetzer R, Krabatsch T, Stepanenko A, Hennig E, Potapov EV. Long-term biventricular support with the HeartWare implantable continuous flow pump. *J Heart Lung Transplant*. 2010;29:822–824. doi: 10.1016/j.healun.2010.02.012.
57. Connellan M, Iyer A, Robson D, Granger E, Dhital K, Spratt P. The HeartWare transvalvular miniature ventricular assist device used for right ventricular support. *J Heart Lung Transplant*. 2013;32(suppl):S149.
58. Schmitto JD, Burkhoff D, Avsar M, Fey O, Ziehme P, Buechler G, Haverich A, Strueber M. Two axial-flow Synergy Micro-Pumps as a biventricular assist device in an ovine animal model. *J Heart Lung Transplant*. 2012;31:1223–1229. doi: 10.1016/j.healun.2012.08.008.
59. Klotz S, Meyns B, Simon A, Wittwer T, Rahmanian P, Schlensak C, Tjan TT, Scheld HH, Burkhoff D. Partial mechanical long-term support with the CirculLite Synergy pump as bridge-to-transplant in congestive heart failure. *Thorac Cardiovasc Surg*. 2010;58(suppl 2):S173–S178. doi: 10.1055/s-0029-1240687. PubMed PMID: 20101535.
60. Meyns B, Klotz S, Simon A, Droogne W, Rega F, Griffith B, Dowling R, Zucker MJ, Burkhoff D. Proof of concept: hemodynamic response to long-term partial ventricular support with the Synergy Pocket Micro-Pump. *J Am Coll Cardiol*. 2009;54:79–86. doi: 10.1016/j.jacc.2009.04.023.
61. Meyns B, Ector J, Rega F, Droogne W, Vanhaecke J, Vanhemelrijck J, Griffith B, Dowling R, Zucker M, Burkhoff D. First human use of partial left ventricular heart support with the Circulite Synergy Micro-Pump as a bridge to cardiac transplantation. *Eur Heart J*. 2008;29:2582. doi: 10.1093/eurheartj/ehn202.
62. Sintek MA, Gdowski M, Lindman BR, Nassif M, Lavine KJ, Novak E, Bach RG, Silvestry SC, Mann DL, Joseph SM. Intra-aortic balloon counterpulsation in patients with chronic heart failure and cardiogenic shock: clinical response and predictors of stabilization. *J Card Fail*. 2015;21:868–876. doi: 10.1016/j.cardfail.2015.06.383.
63. Krishnamoorthy A, DeVore AD, Sun JL, Barnett AS, Samsky MD, Shaw LK, Chiswell K, Patel CB, Patel MR. The impact of a failing right heart in patients supported by intra-aortic balloon counterpulsation [published online ahead of print May 26, 2016]. *Eur Heart J Acute Cardiovasc Care*. 2016. doi: https://doi.org/10.1177/2048872616652262. http://journals.sagepub.com/doi/abs/10.1177/2048872616652262?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub%3dpubmed.
64. Morgan JA, O'Neill WW. Percutaneous right ventricular assist device support in a patient supported by an LVAD. *ASAIO J*. 2016;62:e41–e42. doi: 10.1097/MAT.0000000000000344.
65. Anderson MB, Goldstein J, Milano C, Morris LD, Kormos RL, Bhama J, Kapur NK, Bansal A, Garcia J, Baker JN, Silvestry S, Holman WL, Douglas PS, O'Neill W. Benefits of a novel percutaneous ventricular assist device for right heart failure: the prospective RECOVER RIGHT study of the Impella RP device. *J Heart Lung Transplant*. 2015;34:1549–1560. doi: 10.1016/j.healun.2015.08.018.
66. John R, Long JW, Massey HT, Griffith BP, Sun BC, Tector AJ, Frazier OH, Joyce LD. Outcomes of a multicenter trial of the Levitronix CentriMag ventricular assist system for short-term circulatory support. *J Thorac Cardiovasc Surg*. 2011;141:932–939. doi: 10.1016/j.jtcvs.2010.03.046.
67. Renard BM, Hanson ID, Goldstein JA. Severe mitral regurgitation and biventricular heart failure successfully treated with biventricular percutaneous axial flow pumps as a bridge to mitral valve surgery. *Catheter Cardiovasc Interv*. 2017;89:159–162. doi: 10.1002/ccd.26496.
68. Heinzmann D, Schibilsky D, Gramlich M, Klingel K, Kandolf R, Rosenberger P, Gawaz M, Schreieck J, Schlensak C, Seizer P. Ablation of an electrical storm in a patient with giant cell myocarditis using continuous flow left ventricular assist device and percutaneous right ventricular assist device. *Int J Cardiol*. 2016;209:84–86. doi: 10.1016/j.ijcard.2016.02.060.
69. Fishberger SB, Asnes JD, Rollinson NL, Cleman MW. Percutaneous right ventricular support during catheter ablation of intra-atrial reentrant tachycardia in an adult with a mustard baffle: a novel use of the Impella device. *J Interv Card Electrophysiol*. 2010;29:69–72. doi: 10.1007/s10840-010-9478-4.
70. Kiernan MS, Krishnamurthy B, Kapur NK. Percutaneous right ventricular assist via the internal jugular vein in cardiogenic shock complicating an acute inferior myocardial infarction. *J Invasive Cardiol*. 2010;22:E23–E26.
71. Aggarwal V, Einhorn BN, Cohen HA. Current status of percutaneous right ventricular assist devices: first-in-man use of a novel dual lumen cannula. *Catheter Cardiovasc Interv*. 2016;88:390–396. doi: 10.1002/ccd.26348.
72. Schmack B, Weymann A, Popov AF, Patil NP, Sabashnikov A, Kremer J, Farag M, Brcic A, Lichtenstern C, Karck M, Ruhparwar A. Concurrent left ventricular assist device (LVAD) implantation and percutaneous temporary RVAD support via CardiacAssist Protek-Duo TandemHeart to preempt right heart failure. *Med Sci Monit Basic Res*. 2016;22:53–57. doi: 10.12659/MSMBR.898897.
73. Wang D, Zou X, Liu X, Lick SD, Zwischenberger JB. OxyRVAD for total right heart and respiratory support. *Conf Proc IEEE Eng Med Biol Soc*. 2006;1:5390–5391. doi: 10.1109/IEMBS.2006.260849.
74. Bermudez CA, Lagazzi L, Crespo MM. Prolonged support using a percutaneous OxyRVAD in a patient with end-stage lung disease, pulmonary hypertension, and right cardiac failure. *ASAIO J*. 2016;62:e37–e40. doi: 10.1097/MAT.0000000000000343.
75. Prutkin JM, Strote JA, Stout KK. Percutaneous right ventricular assist device as support for cardiogenic shock due to right ventricular infarction. *J Invasive Cardiol*. 2008;20:E215–E216.
76. Atiemo AD, Conte JV, Heldman AW. Resuscitation and recovery from acute right ventricular failure using a percutaneous right ventricular assist device. *Catheter Cardiovasc Interv*. 2006;68:78–82. doi: 10.1002/ccd.20691.
77. Giesler GM, Gomez JS, Letsou G, Vooletich M, Smalling RW. Initial report of percutaneous right ventricular assist for right ventricular shock secondary to right ventricular infarction. *Catheter Cardiovasc Interv*. 2006;68:263–266. doi: 10.1002/ccd.20846.
78. Takagaki M, Wurzer C, Wade R, Lee R, Malaisrie SC, McCarthy PM, McGee EC Jr. Successful conversion of TandemHeart left ventricular assist device to right ventricular assist device after implantation of a HeartMate XVE. *Ann Thorac Surg*. 2008;86:1677–1679. doi: 10.1016/j.athoracsur.2008.04.101.
79. 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–E229.
80. Hira RS, Thamwiwat A, Kar B. TandemHeart placement for cardiogenic shock in acute severe mitral regurgitation and right ventricular failure. *Catheter Cardiovasc Interv*. 2014;83:319–322. doi: 10.1002/ccd.25107.
81. Bajona P, Salizzoni S, Brann SH, Coyne J, Bermudez C, Kormos R, Toyoda Y. Prolonged use of right ventricular assist device for refractory graft failure following orthotopic heart transplantation. *J Thorac Cardiovasc Surg*. 2010;139:e53–e54. doi: 10.1016/j.jtcvs.2008.10.042.
82. Kapur NK, Paruchuri V, Korabathina R, Al-Mohammdi R, Mudd JO, Prutkin J, Esposito M, Shah A, Kiernan MS, Sech C, Pham DT, Konstam MA, De-

nofrio D. Effects of a percutaneous mechanical circulatory support device for medically refractory right ventricular failure. *J Heart Lung Transplant*. 2011;30:1360–1367. doi: 10.1016/j.healun.2011.07.005.
83. Cheung AW, White CW, Davis MK, Freed DH. Short-term mechanical circulatory support for recovery from acute right ventricular failure: clinical outcomes. *J Heart Lung Transplant*. 2014;33:794–799. doi: 10.1016/j.healun.2014.02.028.
84. Kapur NK, Paruchuri V, Jagannathan A, Steinberg D, Chakrabarti AK, Pinto D, Aghili N, Najjar S, Finley J, Orr NM, Tempelhof M, Mudd JO, Kiernan MS, Pham DT, DeNofrio D. Mechanical circulatory support for right ventricular failure: the TandemHeart in Right VEntricular support (THRIVE) Registry. *JACC Heart Failure*. 2013;1:127–134.
85. Truby L, Mundy L, Kalesan B, Kirtane A, Colombo PC, Takeda K, Fukuhara S, Naka Y, Takayama H. Contemporary outcomes of venoarterial extracorporeal membrane oxygenation for refractory cardiogenic shock at a large tertiary care center. *ASAIO J*. 2015;61:403–409. doi: 10.1097/MAT.0000000000000225.
86. Napp LC, Kühn C, Hoeper MM, Vogel-Claussen J, Haverich A, Schäfer A, Bauersachs J. Cannulation strategies for percutaneous extracorporeal membrane oxygenation in adults. *Clin Res Cardiol*. 2016;105:283–296. doi: 10.1007/s00392-015-0941-1.
87. Aghili N, Kang S, Kapur NK. The fundamentals of extra-corporeal membrane oxygenation. *Minerva Cardioangiol*. 2015;63:75–85.
88. Boulate D, Luyt CE, Pozzi M, Niculescu M, Combes A, Leprince P, Kirsch M. Acute lung injury after mechanical circulatory support implantation in patients on extracorporeal life support: an unrecognized problem. *Eur J Cardiothorac Surg*. 2013;44:544–9; discussion 549. doi: 10.1093/ejcts/ezt125.
89. Fumagalli R, Bombino M, Borelli M, Rossi F, Colombo V, Osculati G, Ferrazzi P, Pesenti A, Gattinoni L. Percutaneous bridge to heart transplantation by venoarterial ECMO and transaortic left ventricular venting. *Int J Artif Organs*. 2004;27:410–413.
90. Koeckert MS, Jorde UP, Naka Y, Moses JW, Takayama H. Impella LP 2.5 for left ventricular unloading during venoarterial extracorporeal membrane oxygenation support. *J Card Surg*. 2011;26:666–668. doi: 10.1111/j.1540-8191.2011.01338.x.
91. Jumean M, Pham DT, Kapur NK. Percutaneous bi-atrial extracorporeal membrane oxygenation for acute circulatory support in advanced heart failure. *Catheter Cardiovasc Interv*. 2015;85:1097–1099. doi: 10.1002/ccd.25791.
92. Kang MH, Hahn JY, Gwon HC, Song YB, Choi JO, Choi JH, Choi SH, Lee SH, Jeon ES. Percutaneous transseptal left atrial drainage for decompression of the left heart in an adult patient during percutaneous cardiopulmonary support. *Korean Circ J*. 2011;41:402–404. doi: 10.4070/kcj.2011.41.7.402.
93. Suguta M, Hoshizaki H, Anno M, Naito S, Tada H, Nogami A, Oshima S, Taniguchi K. Right ventricular infarction with cardiogenic shock treated with percutaneous cardiopulmonary support: a case report. *Jpn Circ J*. 1999;63:813–815.
94. De Silva RJ, Soto C, Spratt P. Extra corporeal membrane oxygenation as right heart support following left ventricular assist device placement: a new cannulation technique. *Heart Lung Circ*. 2012;21:218–220. doi: 10.1016/j.hlc.2011.12.003.
95. Scherer M, Sirat AS, Moritz A, Martens S. Extracorporeal membrane oxygenation as perioperative right ventricular support in patients with biventricular failure undergoing left ventricular assist device implantation. *Eur J Cardiothorac Surg*. 2011;39:939–44; discussion 944. doi: 10.1016/j.ejcts.2010.09.044.
96. Atwater BD, Nee LM, Gimelli G. Long-term survival using intra-aortic balloon pump and percutaneous right ventricular assist device for biventricular mechanical support of cardiogenic shock. *J Invasive Cardiol*. 2008;20:E205–E207.
97. Rajagopal V, Steahr G, Wilmer CI, Raval NY. A novel percutaneous mechanical biventricular bridge to recovery in severe cardiac allograft rejection. *J Heart Lung Transplant*. 2010;29:93–95. doi: 10.1016/j.healun.2009.09.015.
98. Nagy CD, Jumean MF, Pham DT, Kiernan MS, Denofrio D, Kapur NK. Percutaneous circulatory support for biventricular failure. *Circ Cardiovasc Interv*. 2013;6:e12–e14. doi: 10.1161/CIRCINTERVENTIONS.112.000018.
99. Kapur NK, Jumean M, Ghuloom A, Aghili N, Vassallo C, Kiernan MS, DeNofrio D, Pham DT. First successful use of 2 axial flow catheters for percutaneous biventricular circulatory support as a bridge to a durable left ventricular assist device. *Circ Heart Fail*. 2015;8:1006–1008. doi: 10.1161/CIRCHEARTFAILURE.115.002374.
100. Aghili N, Bader Y, Vest AR, Kiernan MS, Kimmelstiel C, DeNofrio D, Kapur NK. Biventricular circulatory support using 2 axial flow catheters for cardiogenic shock without the need for surgical vascular access. *Circ Cardiovasc Interv*. 2016;9:e003636.