Percutaneous Mechanical Circulatory Support Devices in Cardiogenic Shock

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Abstract—Despite a high rate of early revascularization and use of intra-aortic balloon pump counterpulsation therapy, the prognosis of patients with cardiogenic shock has remained poor. In the hopes of improving outcomes, clinicians are increasingly turning to percutaneous left and right mechanical circulatory support devices. Until recently, the evidence base for these devices had consisted only of observational data, meta-analyses, and small feasibility trials. In this article, we describe the contemporary outcomes of patients with cardiogenic shock, the hemodynamics of cardiogenic shock, and hemodynamic effects of percutaneous mechanical circulatory support devices. We then use this discussion to provide clinicians with a useful framework for understanding when selecting between or while managing patients with a percutaneous mechanical circulatory support device. We critically review the recently published data for and against the use of commercially available devices—the intra-aortic balloon pump counterpulsation, the Impella system, the TandemHeart, and venous–arterial extracorporeal membrane oxygenation—and highlight gaps in our understanding. Given such gaps, a consensus multidisciplinary approach that combines expertise from interventional cardiologists, heart failure specialists, cardiac surgeons, and cardiac anesthesiologists may help pair the right patient with the right device at the right time.

Key Words: cardiogenic shock  ■  left ventricular dysfunction  ■  mechanical circulatory support  ■  percutaneous  ■  right ventricular dysfunction

The incidence of cardiogenic shock (CS) is increasing. Data from the Nationwide Inpatient Sample, the largest publicly available all-payer inpatient care database in the United States, show a >2-fold rise in the number of discharges complicated by CS, from 55,123 in 2004 to 126,555 in 2014 (P trend <0.05; Figure 1). Despite a high rate of early revascularization and use of intra-aortic balloon pump counterpulsation (IABP) therapy, the prognosis of patients with CS has remained poor, with 48% of patients in 2014 not surviving to discharge (Figure 1). Rapid innovation in percutaneous left ventricular (LV) and right ventricular (RV) mechanical circulatory support (MCS) devices is fundamentally altering the management of CS, requiring not only technical proficiency with these devices but also novel models of team-based care among cardiologists, cardiac surgeons, heart failure specialists, and cardiac anesthesiologists. The purpose of this article is to review the hemodynamics and outcomes associated with CS, to describe the hemodynamic effects of contemporary MCS devices, and to highlight and review the evidence regarding LV and RV support devices.

Cardiogenic Shock

CS is a state of end-organ dysfunction often attributed to insufficient cardiac output because of LV, RV, or biventricular dysfunction. However, CS is not simply a decrease in cardiac contractile function, but also a multiorgan dysfunction syndrome involving the entire circulatory system, often complicated by a systemic inflammatory response syndrome.1 Interestingly, systemic inflammatory response syndrome scoring systems (eg, Acute Physiology and Chronic Health Evaluation II or SAPS II [Simplified Acute Physiology Score]) and biomarkers of systemic inflammatory response syndrome (interleukin-6 and receptor of advanced glycation end products) can more accurately predict mortality in CS than hemodynamic indices or biomarkers of heart failure.2

Clinically, CS is defined by both hemodynamic parameters (persistent hypotension [systolic blood pressure <80–90 mm Hg or mean arterial pressure 30 mm Hg lower than baseline], a cardiac index (CI) <1.8 L/min/m² without support or <2.0–2.2 L/min/m² with support, and elevated filling pressures [LV end-diastolic pressure >18 mm Hg or RV end-diastolic pressure >10–15 mm Hg]), as well as clinical signs/symptoms of hypoperfusion (cool extremities, decreased urine output, or altered mental status).1

Several cohorts with CS may benefit from the use of percutaneous MCS devices (Table 1). In the United States, acute myocardial infarction (AMI) remains the most common precipitant of CS. From 2003 to 2010, while the incidence of CS complicating AMI rose from 6.5% to 10.1% (P<0.001), inhospital mortality decreased significantly from 44.6% to 33.8% (P<0.001).1 Among patients with congestive heart failure not precipitated by AMI, the incidence of CS rose from 0.5% to

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1.0% ($P<0.001$), while in-hospital mortality decreased significantly from 44.2% to 26.1%.4

**Hemodynamic Effects of MCS Devices**

Current modes of percutaneous MCS can be characterized by 1 of 4 circuit configurations: (1) LV to aorta assist devices (IABP and Impella); (2) left atrium (LA) to systemic artery assist devices (TandemHeart); (3) right atrium (RA) to systemic artery assist devices (venous–arterial extracorporeal membrane oxygenation [V-A ECMO]); and (4) RA to pulmonary artery assist devices (Impella RP and adapted TandemHeart). To varying degrees, all available devices improve cardiac output and blood pressure, but their specific features result in distinct hemodynamic profiles.5 The implications of these differences on clinical outcomes have not yet been studied in adequately powered randomized trials. Contemporarily, commercially available percutaneous LV and RV MCS devices may be seen in Figure 2.

Several key concepts exist that may provide clinicians with a useful framework for understanding when choosing a percutaneous MCS device for a patient or while managing a patient with a percutaneous MCS device. First, derangements in RV systolic and diastolic function and pulmonary vascular resistance have a major impact on the performance characteristics of LV to aorta (IABP therapy and Impella LP) and LA to systemic artery (TandemHeart) assist devices. In these cases, percutaneous V-A ECMO or the combination of an LV assist device with an RV assist device (Impella RP and adapted TandemHeart) may be necessary. Second, IABP therapy and the Impella are associated with significant decreases in total peripheral resistance (TPR) via the lowering of both peak LV systolic and diastolic pressures, as well as improved coronary perfusion, although Impella likely has a greater effect than IABP.6 In contrast, significant flow-mediated increases in TPR are seen with percutaneous V-A ECMO. If TPR and LV
contractility are fixed, the only way for the LV to overcome increased TPR is via increases in the LVEDP, LA pressure, and PCWP. These changes markedly increase myocardial oxygen consumption and may inhibit LV recovery. Thus, except when acute LV recovery is anticipated after initiation of MCS (eg, extracorporeal cardiopulmonary resuscitation [eCPR]), V-A ECMO is most often used as a bridge to bridge or bridge to transplant. While increases in TPR are also seen with the TandemHeart, given that blood is withdrawn directly from the LA, large decreases in the LVEDP, LA pressure, and PCWP are typically seen. Third, continuous pumping of blood from the LV (Impella) results in proportionally greater degrees of LV unloading than pumping from the LA or RA (Tandem Heart).

**LV to Aorta Assist Devices (LV Volume and Pressure Unloading)**

**IABP Counterpulsation Therapy**

Introduced nearly five 5 ago, IABP therapy is commonly used in patients with CS on the assumption that it is associated with hemodynamic improvements, including decreased myocardial oxygen consumption, increased coronary artery perfusion, decreased afterload, and modestly enhanced cardiac output (0.8–1.0 L/min).3 IABP therapy typically requires an 8-Fr sheath in the femoral or axillary artery7 (Table 2).

**IABP Therapy in AMI Patients With CS**

Until recently, the evidence base for IABP therapy in AMI patients with CS had consisted only of observational data22–24 and meta-analyses,22–24 perhaps because few alternatives had been available to support patients with severely compromised hemodynamics.

Prospective randomized controlled trials have failed to demonstrate a conclusive proof of benefit in patients with CS because of AMI.

In 2005, the TACTICS trial (Thrombolysis and Counterpulsation to Improve Cardiogenic Shock) randomized 57 AMI patients with CS status post-fibrinolytic therapy to 48 hours of IABP therapy or optimal medical therapy. The primary end point was all-cause mortality at 6 months. Secondary end points included in-hospital death, reinfarction, and safety events. At 6 months, 43% of the fibrinolysis-only group had died versus 34% of the fibrinolysis–IABP group (P=0.23). Among those patients with Killip class >II, 6-month mortality was significantly lower in the fibrinolysis–IABP group when compared with fibrinolysis only (39% versus 80%, respectively; P=0.05). Similar rates of in-hospital death, reinfarction, and safety events were seen.

Prondzinsky et al randomized 45 AMI patients with CS status postprimary percutaneous coronary intervention (PCI) to IABP therapy or optimal medical therapy.25 The primary end point was change in Acute Physiology and Chronic Health Evaluation II scores over 4 days. Secondary end points included inflammatory markers, brain natriuretic peptide levels, hemodynamic values, and in-hospital mortality. Acute Physiology and Chronic Health Evaluation II scores, interleukin-6 levels, and CI were not significantly different between the cohorts at 4 days, while brain natriuretic peptide levels were lower in patients receiving IABP therapy (suggesting an element of LV unloading). In-hospital mortality was not significantly different between the 2 groups (38.6% versus 28.6% for IABP therapy and optimal medical therapy, respectively; P=ns).

The IABP-SHOCK II trial (Intra-Aortic Balloon Pump in Cardiogenic Shock II) was a multicenter, open-label study that randomized 600 AMI patients with CS of <12 hours duration not because of mechanical causes (eg, ventricular septal defect or papillary muscle rupture) and not requiring cardiopulmonary resuscitation (CPR) for >30 minutes or clinically comatose to IABP therapy or optimal medical therapy.26 Interestingly, no significant differences were seen in the study groups with respect to 30-day mortality (primary outcome; 39.7% in the IABP group versus 41.3% in the optimal medical therapy group) randomized 45 AMI patients with CS status post-fibrinolytic therapy to 48 hours of IABP therapy or optimal medical therapy, respectively; P=0.69) nor time to hemodynamic stabilization, the length of stay in the intensive care unit, serum lactate levels, the dose and duration of catecholamine therapy, renal function, and adverse events (eg, bleeding, stroke, peripheral ischemic complications requiring intervention, or infection). In prespecified subgroup analyses, a significant benefit of IABP therapy was seen only in patients under the age of 50 years and those with a first myocardial infarction. Limitations of this study included its relatively small sample size (>900 patients would have been required to detect the specified treatment effect); the preponderance of more patients with mild to moderate CS (average systolic blood pressure 89 mm Hg and average heart rate 92) compared with other trials and registries, leading to questions about its applicability to more severe CS; a low rate (13.4%) of IABP insertion before PCI (when the risk of hemodynamic compromise is the greatest); the number of crossovers from the optimal medical therapy group to the IABP group (10%), which may have influenced the analysis that was done on an intention-to-treat principle; and lack of longer-term outcomes.
data, especially given that the overall event rate was lower than expected. It remains an important trial, and after its publication, the 2012 ESC Guidelines (European Society of Cardiology) downgraded the use of IABP in ST-segment–elevation myocardial infarction patients with CS from a 1C recommendation to 2B.27 The 2013 American College of Cardiology/American Heart Association guidelines, which do not incorporate the results of the IABP-SHOCK II trial, maintain IABP therapy as a 2A recommendation in ST-segment–elevation myocardial infarction patients with CS.28

Recent meta-analyses of IABP therapy in AMI patients with CS (incorporating the results of the IABP-SHOCK II trial) have further called into question the utility of IABP therapy in these patients. Analyzing data from 17 studies, Romeo et al29 reported no overall differences in short- or long-term mortality in patients receiving IABP therapy. Interestingly, when stratified by initial treatment, IABP therapy significantly reduced mortality (RR, 0.77; 95% CI, 0.68–0.87) in patients receiving thrombolytic therapy but significantly increased mortality (RR 1.18, 95% CI 1.04–1.34) in patients receiving primary PCI. More recently, using data from 12 randomized controlled trials and 15 observational studies, Ahmad et al30 reported no benefit of IABP therapy in AMI on 30-day mortality, regardless of the presence (odds ratio [OR], 0.94; 95% CI, 0.69–1.28) or absence (OR, 0.98; 95% CI, 0.57–1.69) of CS.

IABP Therapy in Advanced Heart Failure Patients With CS

While limited to small single-center studies, IABP therapy in advanced heart failure patients with CS seems to be a reasonable bridge to more advanced therapies.

Gjesdal et al31 compared the outcomes of 32 patients with advanced heart failure treated with IABP therapy as a bridge to transplantation with 135 electively transplanted patients. The mean duration of IABP therapy was 21±16 days, and 80% of patients survived to transplant without additional MCS. Three patients developed vascular complications, 2 patients developed sepsis, and 1 patient developed ileus, corresponding to 0.05 complications per patient-week of support. Most notably, mortality was similar in the IABP and electively transplanted cohorts at 1 year (9.4% versus 11.1%; P=0.80).

More recently, axillary IABPs have generated considerable interest because they permit ambulation and limit debility during the waiting period for advanced therapies. Among 50 patients with end-stage heart failure awaiting transplantation, 92% survived to transplantation on left axillary–subclavian artery IABP support for a median of 18 days. Ninety-day posttransplant survival was 90%.33 Prior to transplant, patients received a median of 3 (2–15) nursing-guided ambulation sessions. No significant bleeding or arterial ischemic complications were seen at the time of IABP placement. Prior to transplantation, 2 patients required surgical evaluation.
for acquired left-hand ischemia and 3 patients underwent removal of the IABP secondary to axillary IABP complications. IABP removal was followed by percutaneous closure with an 8-Fr Angioseal device in 58% of patients. Similarly, Tanaka et al\textsuperscript{35} reported outcomes in 88 patients with end-stage heart failure awaiting transplantation who received axillary–subclavian IABP therapy. Eighty percent of patients had their IABPs surgically implanted in the right subclavian artery. The median duration of IABP support was 21 days (maximum 135 days). 93.2% of patients survived to recovery, transplantation, or durable mechanical support. 95.5% of patients ambulated extensively and demonstrated a significant increase in their aerobic capacity, as assessed by the 2-minute step-in-place test. Access site complications (hematomas, infection, and asymptomatic bleeding) occurred in 8 (9.1%) patients.

### Impella

The Impella (Abiomed, Danvers, MA) is a continuous, nonpulsatile, axial flow Archimedes-screw pump that provides active support by expelling aspirated blood from the LV into the ascending aorta (Figure 2). Importantly, unlike IABP therapy, the Impella does not require EKG or arterial waveform triggering, facilitating stability even in the setting of tachyarrhythmias or electromechanical disassociation. However, careful patient selection and meticulous attention to good technique are critical given reported complications, which include device migration, device malfunction because of thrombosis, hemolysis, bleeding requiring transfusion, arrhythmias, limb ischemia, tamponade, aortic or mitral valve injury, and stroke.\textsuperscript{36,37}

Three versions for LV support are currently available: the Impella LP 2.5 that can deliver 2.5 L/min of CO, and the Impella LP 5.0 that can deliver 5.0 L/min of CO. While the Impella LP 2.5 and Impella CP can be delivered percutaneously via a 12- to 14-Fr sheath, insertion of the Impella LP 5.0 requires surgical cut down of the femoral or axillary artery prior to insertion of a 22-Fr sheath.

### Impella Therapy in AMI Patients With CS

The ISAR-SHOCK trial (Impella LP 2.5 Versus IABP in Cardiogenic Shock) was a 2-center, randomized controlled pilot study that randomized 26 AMI patients with CS to hemodynamic support with the Impella LP 2.5 or IABP therapy.\textsuperscript{38} The primary end point was change in CI from baseline to 30 minutes after implantation. Secondary end points included lactic acidosis, hemolysis, and mortality after 30 days. While the CI after 30 minutes of support was significantly increased in patients with the Impella LP 2.5 compared with patients with IABP therapy (0.49±0.46 versus 0.11±0.31 L/min/m\textsuperscript{2}, respectively; \(P=0.02\)), no significant differences were seen by 4 hours in the CI, modified cardiac power index, or serum lactate. By 24 hours, no significant differences were seen in urine output, vasopressor dose, median vasopressor support time, or mechanical ventilation support time. Hemolysis and packed red blood cell or fresh frozen plasma administration were significantly higher in patients with the Impella LP 2.5, and 1 case of acute limb ischemia requiring surgery after device explanation was seen. Overall, 30-day mortality was 46% in both groups. The most obvious limitation of this pilot study was its small number of patients, which precluded a meaningful evaluation of potential mortality differences.

More recently, Ouweneel et al\textsuperscript{36} reported results from the IMPRESS trial (Impella CP Versus Intra-Aortic Balloon Pump
In Acute Myocardial Infarction Complicated by Cardiogenic Shock, which randomized 48 AMI patients with CS to hemodynamic support with the Impella CP or IABP therapy. Device placement occurred at the discretion of the treating physician, either prior to PCI, during PCI, or immediately after PCI. The primary and secondary end points were 30-day and 6-month mortality, respectively. Notably, 92% of study population had a history of recent cardiac arrest requiring resuscitation. At 30 days, mortality was similar (50% versus 46% for patients receiving support with the Impella CP or IABP therapy, respectively; \( P=0.92 \)). Six-month mortality was 50% in both groups. More bleeding events (8 versus 2) occurred in patients receiving support with the Impella CP than in the IABP group, respectively, and significant hemolysis requiring the cessation of Impella CP therapy occurred in 2 patients.

Impella Therapy in Postcardiotomy Patients With CS

The RECOVER I feasibility study evaluated the safety and efficacy of the Impella LD 5.0 in postcardiotomy CS patients. In 16 patients, the Impella LP 5.0 significantly improved hemodynamic indices after insertion and was associated with 94%, 81%, and 75% survival at 30 days, 6 months, and 1 year, respectively. The primary safety end point (a composite of death and stroke) occurred in 2 patients. Other complications included bleeding requiring reoperation (7 patients), sepsis (6 patients), renal failure (3 patients), hepatic failure (1 patient), and major vascular injury (1 patient).

IABP Therapy in Advanced Heart Failure Patients With CS

In a single case series, the Impella LP 5.0 has been shown to be effective as a bridge to transplantation, a bridge to bridge, and a bridge to recovery.

LA to Systemic Artery-Assist Devices (LV Volume Unloading)

TandemHeart

The TandemHeart (TandemLife, Pittsburgh, PA) provides MCS of \( \leq 4 \) L/min via a continuous flow centrifugal pump. Oxygenated blood is withdrawn from the LA via a 21-Fr inflow cannula placed via transseptal puncture and then reinjected into the lower abdominal aorta or iliac arteries via a 15- to 17-Fr outflow cannula (Figure 2). The TandemHeart is inserted through the femoral vein and is advanced across the interatrial septum into the LA. The need for transseptal puncture is a potential limitation for operators not facile with this technique.

TandemHeart Therapy in AMI Patients With CS

In 2005, Thiele et al reported their early experience with TandemHeart therapy in AMI patients with CS. Forty-one AMI patients with CS were randomized to hemodynamic support with either IABP therapy or the TandemHeart. The primary end point was hemodynamic improvement (as measured by the cardiac power index). Secondary end points included 30-day mortality and safety end points. While greater improvements in cardiac power index, CI, pulmonary artery pressure, and PCWP were seen in patients receiving the TandemHeart, 30-day mortality was similar (43% versus 45%; \( P=0.86 \)) in both groups. In the TandemHeart cohort, 7 patients (33%) developed limb ischemia requiring intervention (IABP \( n=0; \ P=0.009 \)). Nineteen patients (90%) required blood transfusions (median 8.0 U, interquartile range, 3.8–16.5 U; IABP \( n=8; \ P=0.002 \)), and 13 patients (62%) had signs of disseminated intravascular coagulation (IABP \( n=3; \ P=s= \)).

The TandemHeart Investigators Group randomized 33 AMI patients with CS to treatment with IABP therapy or the TandemHeart. Major exclusion criteria included coagulopathy, sepsis, stroke within 6 months, severe peripheral vascular disease, isolated right heart failure, \( \geq 2+ \) aortic regurgitation, and ventricular septal rupture. The primary end point was hemodynamic changes. Secondary end points included safety and 30-day mortality. Compared with IABP therapy, patients receiving the TandemHeart had significantly greater increases in CI (0.6±0.6 versus 1.2±0.8 L/min, respectively) and significantly greater decreases in PCWP over the first 16 hours. The percentage of patients with at least 1 adverse event was not significantly different between patients receiving IABP therapy and the TandemHeart (\( P=0.12 \)), with bleeding being the most common adverse event in both groups. Thirty-day mortality was 36% in the IABP group compared with 47% in the TandemHeart group (\( P=ns \)).

In 2011, Kar et al reported outcomes after TandemHeart therapy in 80 AMI patients with CS. Notably, almost half of these patients had undergone CPR immediately before or at the time of implantation. TandemHeart therapy was associated with significant improvements in hemodynamic indices. The 30-day and 6-month mortality rates were 40.2% and 45.3%, respectively. Notably, 1 patient died after wire-mediated perforation of the LA. Other complications included the need for blood transfusions (71%), sepsis/systemic inflammatory response syndrome (29.9%), bleeding around the cannula (29.1%), gastrointestinal bleeding (19.7%), coagulopathy (11%), stroke (6.8%), and device-related limb ischemia (3.4%).

TandemHeart Therapy in Advanced Heart Failure Patients With CS

Kar et al also reported outcomes after TandemHeart therapy in 37 nonischemic cardiomyopathy patients with CS. In the nonischemic cardiomyopathy group, the 30-day and 6-month mortality rates were 32% and 35%, respectively (when compared with ischemic cardiomyopathy; \( P=ns \)). Fewer blood transfusions were needed (35.1% versus 71%) in patients with nonischemic cardiomyopathy when compared with patients with ischemic cardiomyopathy. The TandemHeart has been validated in smaller case series as a bridge to transplantation, bridge to bridge, bridge to decision, and bridge to recovery.

RA to Systemic Artery Assist Devices (Biventricular Pressure and Volume Unloading)

Venous–Arterial Extracorporeal Membrane Oxygenation

While the use of ECMO has increased from 2004 to 2014 (\( P=0.004 \)), outcomes remain poor, with an in-hospital mortality of 47% in 2014 (Figure 3).

In peripheral V-A ECMO, blood is aspirated via a 18- to 21-Fr venous inflow cannula in the femoral or internal jugular vein, directed into a membrane oxygenator, and returned to
the arterial system via a 15- to 22-Fr outflow cannula in the femoral or axillary artery, thereby, bypassing the heart and lungs and providing MCS of >4.5 L/min (Figure 2).

There are 2 important caveats to its use. First, despite adequate peripheral unloading, venous blood return to the left heart (primarily from the bronchial circulation) in the setting of peripheral flow-mediated elevated TPR can result in blood pooling in the LV and, thereby, elevated LV pressures. The clinical consequences of this may include LV thrombus, as well as pulmonary edema. While concomitant IABP therapy to vent the LV does not improve outcomes in patients receiving V-A ECMO, IABP therapy does effectively lower pulmonary artery pressures and decrease LV dimensions. Cheng et al have reported the use of the Impella 2.5 as an LV vent in patients on V-A ECMO with evidence of LV distension, resulting in a decreased LVEDD as measured by echocardiography (7.8±1.4 cm versus 6.2±0.8 cm; P=0.001). Other approaches include percutaneous atrial septostomy (to allow left-to-right shunting) or a surgically placed LV vent.

Second, if femoral artery cannulation is chosen, steps must be taken to ensure the adequate retrograde flow of extracorporeally oxygenated blood into the arch and proximal ascending aorta to ensure delivery to the cerebral vessels and coronary arteries. This is especially important as native cardiac function recovers and the mixing of anterograde deoxygenated (in patients with respiratory failure) blood and retrograde (extracorporeally) oxygenated blood occurs. The serial monitoring of right upper extremity oxygen saturations and EKGs (for ST-T changes) may provide information on cerebral and cardiac oxygenation, respectively.

**V-A ECMO in AMI Patients With CS**

The evidence base for V-A ECMO in AMI patients with CS not requiring CPR consists largely of small, single-center case series. The limitations of such single-center studies include patient selection bias, variability in the timing of support, and the lack of a control group. Despite these limitations, the use of V-A ECMO in AMI patients with CS has been associated with improved survival and reduced rates of LV thrombus formation.

**Figure 3.** We queried the 2004 to 2014 Nationwide Inpatient Sample databases to identify all patients undergoing extracorporeal membrane oxygenation (ECMO; International Classification of Diseases-Ninth Revision [ICD-9] CM 39.65). The Mantel–Haenszel X² test was used to analyze trends. **A,** ECMO was used in 1653 patients in 2004 and 6890 patients in 2014 (P=0.005). **B,** In-hospital mortality was stable between 2004 and 2014 at 47% (P=0.80).
series. In the largest of these, Muller et al\textsuperscript{51} assessed clinical and quality of life outcomes in 138 AMI patients with CS not requiring CPR receiving V-A ECMO. 47%, 41%, and 38% of patients were alive at discharge, 6 months, and 1 year, respectively. ECMO was a bridge to bridge in 18 patients and a bridge to transplant in 13 patients. ECMO-associated complications (leg ischemia, femoral hemorrhage because of arterial laceration, cannula insertion-site infection, pulmonary edema, and circuit-related hemolysis) occurred in 39% of patients.

V-A ECMO can also be considered in AMI patients with CS experiencing a cardiac arrest who remain refractory to initial resuscitative efforts, so called eCPR.\textsuperscript{52–56} In 2008, Chen et al\textsuperscript{55} reported outcomes for 178 in-hospital cardiac arrest patients (117 patients diagnosed with AMI) receiving conventional CPR or eCPR. After propensity matching, there was still a significant difference in survival to discharge (HR, 0.51; 95% CI, 0.35–0.74), 30-day survival (HR, 0.47; 95% CI, 0.28–0.77), and 1-year survival (HR, 0.53; 95% CI, 0.33–0.83; \( P = 0.006 \)) favoring eCPR over conventional CPR. Thiggarajan et al\textsuperscript{56} analyzed 295 patients (75% with AMI) in the ELSO registry (Extracorporeal Life Support Organization) receiving eCPR and reported a survival of 27% in patients otherwise facing imminent mortality. Similarly, Kagawa et al\textsuperscript{53} reported single-center outcomes in 86 patients with AMI who were unresponsive to conventional CPR. Emergency coronary angiography was performed in 81 patients (94%), and intra-arrhythmia PCI was performed in 61 patients (71%). The rates of return of spontaneous circulation, 30-day survival, and favorable neurological outcomes were 88%, 29%, and 24%, respectively.

**V-A ECMO in Postcardiotomy/Advanced Heart Failure Patients With CS**

V-A ECMO has been used in patients with CS because of acute myocarditis, primary graft dysfunction, rejection, and as a bridge to bridge or bridge to transplant.\textsuperscript{57,58}

Combes et al\textsuperscript{57} analyzed 65 patients receiving V-A ECMO (72% of patients were cannulated percutaneously) for CS secondary to dilated cardiomyopathy (n=18), fulminant myocarditis (n=16), postcardiotomy (n=16), post-transplantation (n=10), and miscellaneous (n=5). Peripheral ECMO was switched to central ECMO in 3 patients (6%) because of leg ischemia or inadequate support. In-hospital mortality was 58%. The majority of patients (57%) experienced >1 major ECMO-related complication, including major bleeding (32%), femoral vein thrombosis (10%), arterial ischemia (19%), vena cava thrombosis (7.4%), surgical wound infection (17%), pulmonary edema (12%), and stroke (8.6%). Rastan et al\textsuperscript{59} reported outcomes for 517 patients requiring V-A ECMO after cardiac surgery. Two hundred and three (29.2%) patients were cannulated percutaneously. The mean duration of ECMO support was 3.28±2.85 days. Weaning from ECMO was successful in 63.3% of patients, and 24.8% of patients were discharged. Cumulative survival after 6 months, 1 year, and 5 years were 17.6%, 16.5%, and 13.7%, respectively. Risk factors for hospital mortality were age >70 years (OR, 1.6; 95% CI, 1.01–2.69; \( P = 0.049 \)), diabetes mellitus (OR, 2.47; 95% CI, 1.48–4.13; \( P = 0.001 \)), and renal insufficiency (OR, 2.11; 95% CI, 1.04–4.29; \( P = 0.038 \)). No differences in mortality were seen between patients undergoing central or peripheral cannulation. Complication rates were similar to those described by Combes et al.\textsuperscript{57}

**RA to Pulmonary Artery Assist Devices**

Acute RV failure may occur in multiple settings, including AMI, fulminant myocarditis, acute decompensated heart failure, acute pulmonary embolism, decompensated pulmonary hypertension, postcardiotomy, orthotopic heart transplant, and increasingly after left ventricular assist device (LVAD) implantation. When acute RV failure occurs, the mainstays of therapy include inotropic and pulmonary vasodilator support and the optimization of volume status.

Temporary mechanical support devices for RV failure are an attractive option because RV function often improves sufficiently (albeit over days to weeks) to allow for device removal.

**RV Pressure Unloading**

The RECOVER RIGHT study (Impella RP Right Ventricular Heart Failure Trial) evaluated the safety and efficacy of the Impella RP (4.0 L/min of cardiac support) in 30 patients with RV failure refractory to medical therapy.\textsuperscript{60} For the purposes of analysis, the cohort was divided into patients with RV failure after LVAD implantation and patients with RV failure after AMI or cardiomyotony. At baseline, patients were on an average of 3.2 inotropes/pressors. Major exclusion criteria included patients with INTERMACS (Interagency Registry for Mechanically Assisted Circulatory Support) Profile 1 (crash and burn), anoxic brain injury, right heart thrombus, right heart prosthetic valves, severe pulmonary hypertension, mechanical complications after AMI, and patients supported with a surgical right ventricular assist device or ECMO. The primary end point was survival to 30 days or hospital discharge (whichever was longer). Secondary end points included safety parameters. The primary end point was achieved in 73.3% of the overall study population, with 83.3% of patients with RV failure after LVAD implantation and 58.3% of patients with RV failure after AMI or cardiomyotony alive at 30 days or discharge. All discharged patients were alive at 180 days. Bleeding occurred in 60% of patients and hemolysis occurred in 13% patients, with no differences seen between the cohorts. These results are particularly compelling when considering that prior studies of right ventricular assist devices in patients with CS reported survival rates of 42% to 57% to discharge.\textsuperscript{61,62}

In 2015, based on the data above, the Impella RP received humanitarian device exemption approval from the Food and Drug Administration for adult or pediatric patients with a body surface area ≥1.5 m\textsuperscript{2} who develop acute RV failure after LVAD implantation, AMI, heart transplantation, or cardiomyotony.
(50% versus 62%; \(P=0.4\)) and highest among patients with RV failure with acute myocarditis (100%), after valve surgery (87%), or after CABG (67%) and lowest among patients with RV failure after orthotopic heart transplant (40%), AMI (33%), chronic LV failure (33%), and LVAD implantation (20%). Thrombolysis in myocardial infarction-major bleeding was seen in 41% of patients cannulated percutaneously, with 1 patient developing a retroperitoneal bleed.

Conclusions

While the pace of innovation in percutaneous left and right MCS devices has accelerated recently, the available evidence for or against their use in CS is sparse, often comprised of observational studies with surrogate end points, and outcomes remain poor. Any attempt to improve outcomes in CS should begin with its early identification. Models of care, including a multidisciplinary CS team,62 hold potential in speeding the early identification and treatment of CS.

Among the many challenges that remain include how best to pair the right patient with the right device at the right time. AMI patients with CS seem to have the worst prognosis, while patients with CS status postcardiac surgery with acute RV failure seem to fare the best. Data from the above-mentioned studies with a focus on the time course of CS indicates that percutaneous MCS has a limited ability to change outcome if initiated when overt multiorgan dysfunction has already occurred. Accordingly, perhaps MCS should not be considered the treatment of last resort in AMI patients with CS but should probably be initiated early in the disease course (pre-PCI). Supporting data for this, however, beyond a single study from the US Pella investigators initiation where outcomes were improved when MCS was initiated prior to reperfusion17 is currently lacking. The ongoing Door to Unloading with Impella CP System in Acute Myocardial Infarction to Reduce Infarct Size prospective, multicenter trial may shed further light on this issue.

While randomization in CS poses logistical and ethical challenges, randomized controlled trials of percutaneous MCS devices with clinical not surrogate end points and long-term follow-up are urgently needed, especially given that their use has risen just as quickly as IABP therapy use has fallen. Significant research opportunities remain.

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None.

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