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Periprocedural Cardiopulmonary Bypass or Venoarterial Extracorporeal Membrane Oxygenation During Transcatheter Aortic Valve Replacement: A Systematic Review

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***Background*—**There are limited data on the use of venoarterial extracorporeal membrane oxygenation (VA-ECMO) or cardiopulmonary bypass (CPB) to provide hemodynamic support periprocedurally during transcatheter aortic valve replacement. This study sought to evaluate patients receiving transcatheter aortic valve replacement with concomitant use of CPB/VA-ECMO.

***Methods and Results*—**We systematically reviewed the published literature from 2000 to 2018 for studies evaluating adult patients requiring CPB/VA-ECMO periprocedurally during transcatheter aortic valve replacement. Studies reporting short-term and long-term mortality were included. Given the significant methodological and statistical differences between published studies, meta-analysis of the association of CPB/VA-ECMO with mortality was not performed. Of the 537 studies identified, 9 studies representing 5191 patients met our inclusion criteria. Median ages were between 75 and 87 years with 33% to 75% male patients. Where reported, the Edwards SAPIEN™ transcatheter heart valve was the most frequently used. A total of 203 (3.9%) patients received periprocedural hemodynamic support with CPB/VA-ECMO. Common indications for CPB/VA-ECMO included left ventricular or aortic annular rupture, rapid hemodynamic deterioration, aortic regurgitation, cardiac arrest, and left main coronary artery obstruction. The use of CPB/VA-ECMO was predominantly an emergent strategy and was used for durations of 1 to 2 hours. Short-term mortality (in-hospital and 30-day) was 29.8%, and 1-year mortality was 52.4%. Major complications such as bleeding, vascular injury, tamponade, stroke, and renal failure were noted in 10% to 50% of patients.

***Conclusions*—**CPB/VA-ECMO was used in 4% in the early experience of patients undergoing transcatheter aortic valve replacement, most commonly for periprocedural complications. There are limited data on preprocedural planned use of VA-ECMO, and the characteristics of this population remain poorly defined. **(*J Am Heart Assoc*. 2018;7:e009608. DOI: 10.1161/JAHA.118.009608.)**

Key Words: cardiogenic shock • cardiopulmonary bypass • critical care • mechanical circulatory support • transcatheter valve implantation

The introduction of transcatheter aortic valve replacement (TAVR) into clinical practice has revolutionized the management of aortic stenosis since its approval by the Food and Drug Administration in 2011.[1] This was initially offered as an alternative to surgical aortic valve replacement in patients with a high risk for cardiac surgery but has subsequently expanded to encompass intermediate-risk populations.[1-3] With improving expertise in patient selection and procedural competence, the TAVR technology is being increasingly offered to patients with higher age, frailty, and comorbidity profiles.[4] As noted in a recent study from the Transcatheter Valve Therapy registry, between 2012 and 2014, TAVR was offered to nearly 10% of patients on an urgent/emergent basis.[4] These populations, among others, are at a high risk of preoperative hemodynamic instability and perioperative hemodynamic deterioration, particularly when they present at a later stage of the aortic stenosis disease progression.[4]

In the catheterization laboratory, mechanical circulatory support (MCS) devices are often used as hemodynamic adjuncts for coronary, structural, and electrophysiological procedures.[5-7] There have been multiple studies evaluating unselected MCS devices in the perioperative management of

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Accompanying Data S1 and Table S1 are available at http://jaha.ahajournals.org/content/7/14/e009608/DC1/embed/inline-supplementary-material-1.pdf

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Clinical Perspective

What Is New?

- In this systematic review of 9 studies, venoarterial extracorporeal membrane oxygenation was used in 4% in the early experience of patients undergoing transcatheter aortic valve replacement, most commonly for periprocedural complications with limited information on preprocedural indications and planning.

What Are the Clinical Implications?

- Further dedicated studies are needed to define the preprocedural role of patient, procedural, and device factors in the use of venoarterial extracorporeal membrane oxygenation before transcatheter aortic valve replacement.

TAVR patients.[7] Despite the concomitant use of both TAVR and cardiorespiratory support using the cardiopulmonary bypass (CPB) machine or the venoarterial extracorporeal membrane oxygenation (VA-ECMO) technologies over the past decade, there are limited data on the indications, procedural characteristics, complications, and outcomes of these patients.[8] In this systematic review we sought to analyze the clinical profile, indications, complications, device parameters, and mortality outcomes in TAVR patients needing CPB/VA-ECMO.

Material and Methods

Data Sources and Search Strategies

This study was performed using publicly available data from published literature. The data, analytic methods, and study materials have been made available to other researchers for purposes of reproducing the results or replicating the procedure (Data S1). A comprehensive search of several databases (Ovid MEDLINE Epub Ahead of Print, Ovid Medline In-Process & Other Non-Indexed Citations, Ovid MEDLINE, Ovid EMBASE, Ovid Cochrane Central Register of Controlled Trials, Ovid Cochrane Database of Systematic Reviews, and Scopus) from 2000 to February 9, 2018 was conducted. The search strategy was designed and conducted by a medical librarian with input from the study's first author. Controlled vocabulary supplemented with keywords was used to search for mortality outcomes in adult patients needing CPB/VA-ECMO before or after TAVR. The detailed search strategy is presented in Data S1. The resultant abstracts were screened by 2 independent reviewers (H.P., H.S.). All references of included studies were evaluated for additional studies. Study inclusion was based on the consensus of the 2 reviewers. A third independent reviewer (Saarwaani V.) served as the referee in case of disagreement between the first 2 reviewers in conjunction with the first author (Saraschandra V.). The search strategy and reporting were performed using STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines.[9]

Inclusion and Exclusion Criteria

Studies that included adult (>18 years) patients undergoing TAVR procedures with the use of perioperative CPB/VA-ECMO were included. Case-control, cohort, case series, and randomized trial study designs were included. In studies reporting outcomes in unselected TAVR patients, only studies for which a 2×2 table could be constructed between CPB/VA-ECMO and mortality were included. Abstracts presented at professional societal meetings were excluded because they are subject to a higher risk of bias due to lack of rigorous peer review. Case reports, systematic or narrative reviews, pediatric or animal studies, and studies without relevant outcomes were excluded. If multiple studies were published by the same group of authors over the same study duration, only the largest study with relevant outcomes was included. Data abstracted included study year, population, location, type of study, CPB/VA-ECMO–related parameters, TAVR-related parameters, echocardiography data, and clinical outcomes. Quality was assessed using the Newcastle Ottawa Scale (http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp).

Given the significant methodological and statistical differences among published studies, meta-analysis of the association of CPB/VA-ECMO with mortality was not performed. Therefore, available evidence was summarized using systematic review methodology.

Results

The search strategy identified 537 unique abstracts. Of those, 9 studies representing a total of 5191 patients met the inclusion criteria (Figure and Table 1).[8,10–17] All studies except the study by Seco et al[15] were retrospective studies of institutional or national databases. All studies were published from 2012 to 2017, with 7 out of 9 studies published from the United States and Europe. All studies demonstrated a low risk of bias (Newcastle Ottawa Scale >3) (Table S1). As noted in Table 1, the median ages across the studies varied between 75 to 87 years with 33% to 75% male patients. The aortic valve echocardiographic parameters were reflective of severe aortic stenosis (valve area <1.0 cm^2 and average mean gradient >40 mm Hg) (Table 2). Where reported, the Edwards SAPIEN transcatheter heart valve was the most frequently used. This was the only valve in the PARTNER (Placement of Aortic Transcatheter Valves) trial, which contributed the most

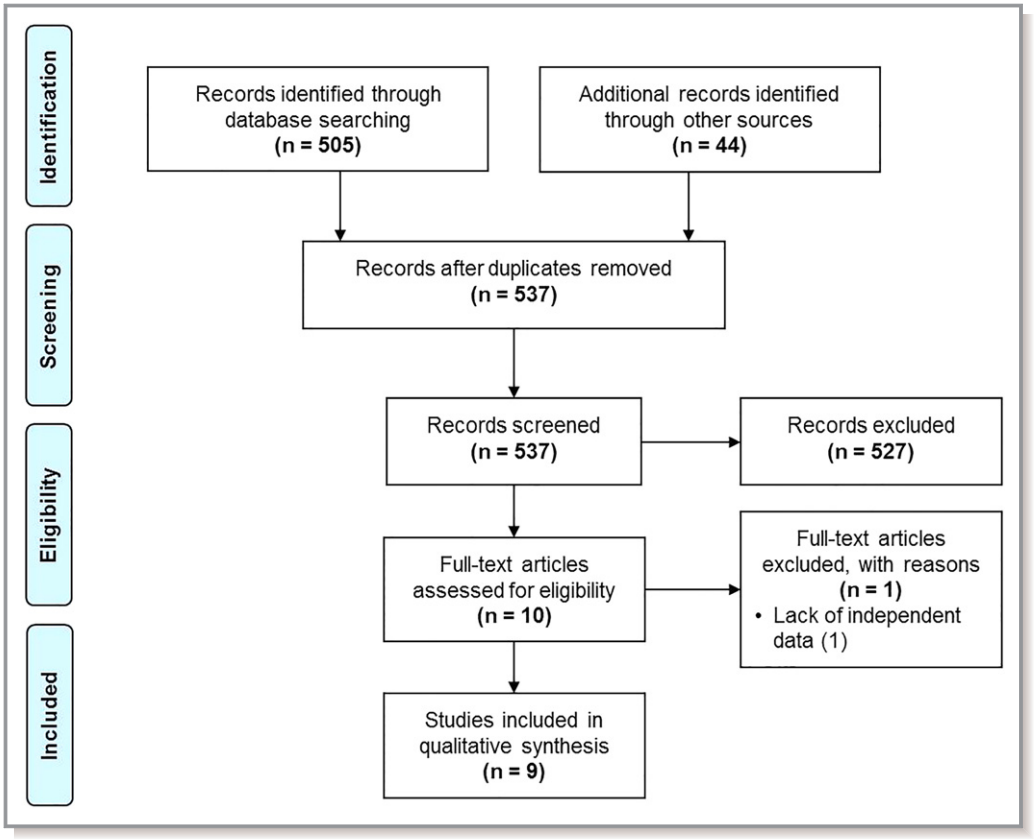

Figure. Literature search strategy.

patients to this systematic review.[8] As noted in Table 2, a majority (≥67%) of the TAVR procedures were performed by a transfemoral approach, except in the study by Uehara et al,[17] in which only 14% were performed transfemorally.

Of the 5191 TAVR patients in these 9 studies, 203 (3.9%) received periprocedural hemodynamic support with CPB/VA-ECMO. The substudy of the PARTNER trial registry by Shreenivas et al was the largest study, contributing 109/203 (53.7%) patients, all of whom needed CPB.[8] Commonly noted indications for CPB/VA-ECMO included left ventricular (LV) or aortic annular rupture, rapid hemodynamic deterioration, severe aortic regurgitation, cardiac arrest from ventricular tachycardia or fibrillation, and obstruction of the left main coronary artery.[8,10-17] The definition of hemodynamic deterioration varied across studies and included low cardiac output, need for high-dose vasopressors and inotropes, prolonged pacing sequence, and severe LV dysfunction on echocardiography. Only the study by Seco et al specified criteria for prophylactic use of VA-ECMO before TAVR as heart failure hospitalization pre-TAVR, moderate to severe biventricular failure, and hemodynamic instability during balloon aortic valvuloplasty in addition to objective hemodynamic data.[15]

In the studies that reported prophylactic versus emergent use, a varying percentage of 17% to 73% of patients needed prophylactic CPB/VA-ECMO support. The use of CPB/VA-ECMO was predominantly an emergent strategy and used for durations of 1 to 2 hours except as noted in Table 3. All but 3 patients had peripheral implantation of VA-ECMO in the studies that reported these data.[11,17] Major complications such as bleeding, vascular injury, tamponade, stroke, and renal failure were noted with varying frequency of 10% to 50% across the studies. Short-term mortality (in-hospital and 30-day) was 29.8% (28/94 patients), and 1-year mortality was 52.4% (78/149). Short-term mortality (0-46%) and 1-year mortality was (14-58%) varied widely among studies.

Discussion

In this systematic study, preprocedural or postprocedural CPB/VA-ECMO was used in 4% in the early experience of patients undergoing TAVR, primarily as an emergent strategy for procedural complications. Short-term mortality (in-hospital or 30-day mortality) was 29.8% and 1-year mortality was 52.4% in TAVR patients requiring VA-ECMO or CPB. Due to the improvements in device technology, technique, and success rates, TAVR has evolved into a relatively low-risk procedure despite the high comorbidity and relative frailty of patients needing this procedure.[18] As noted in a recent article, less than 5% of all TAVR procedures require conversion to open surgery, making this procedure both safe and feasible in high-

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Table 1. Study Characteristics

	Study Characteristics				Patients Needing CPB/VA-ECMO			
Author/Year	Country	Design	Number	Mortality End Point	Number	Indications	Age (y) Median±SD	Male, N (%)
Arlt 2012[10]	Germany	Retrospective	14	In hospital	4	Cardiorespiratory arrest	79.7±5.6	3 (75)
Banjac 2016[11]	United States	Retrospective	230	In hospital	10	LV perforation, VF/VT, aortic rupture, valve embolization, left main impingement, prolonged pacing, severe AR	83±8	5 (50)
Dolmatova 2017[12]	United States	Retrospective	247	In hospital	6	VF, respiratory failure, LV perforation, aortic annulus rupture	82±7.4	2 (33.3)
Husser 2013[13]	Germany	Retrospective	214	30-d	18	LV perforation, cardiogenic shock, VF/VT, severe LV dysfunction, prolonged pacing, high-dose vasopressors, high-risk left main coronary intervention	80±5	9 (50)
Pontailler 2017[14]	France	Retrospective	5	30-d	5	Tamponade, hemorrhagic shock, MI, LV dysfunction	NA	NA
Seco 2014[15]	Australia	Prospective	100	30-d	11	*Prophylactic*: Heart failure hospitalization pre-TAVR, moderate/severe LV/RV failure, hemodynamic instability during balloon aortic valvuloplasty before TAVR, CVP or PCWP >20 mm Hg, mPAP >40 mm Hg, CI <2.0 L/min per m^2. *Rescue*: VF causing cardiogenic shock, aortic annulus rupture/tamponade with hemodynamic deterioration	75.7±9.11	8 (73)
Shreenivas 2015[8]	United States	Prospective registry	2525	1-y	109	Cardiogenic shock	NA	NA
Trenkwalder 2017[16]	Germany	Retrospective	1810	In hospital, 30-d, 1-y	33	LV perforation, low cardiac output, hemorrhage, coronary artery impingement, ventricular arrhythmias, severe AR, aortic annulus rupture, aortic dissection	80.5±5.4	14 (42.4)
Uehara 2017[17]	Japan	Retrospective	46	In hospital, 30-d, 1-y	7	Sudden systolic blood pressure decrease, mPAP elevation, VF, severe LV dysfunction	87.3±3.6	NA

AR indicates aortic regurgitation; CI, cardiac index; CPB, cardiopulmonary bypass; CVP, central venous pressure; LV, left ventricular; MI, myocardial infarction; mPAP, mean pulmonary artery pressure; NA, not available; PCWP, pulmonary capillary wedge pressure; RV, right ventricle; TAVR, transcatheter aortic valve replacement; VA-ECMO, venoarterial extracorporeal membrane oxygenation; VF, ventricular fibrillation; VT, ventricular tachycardia.

Table 2. Characteristics of TAVR Patients Receiving Cardiopulmonary Support

	Risk Scores		Echocardiographic Characteristics				TAVR Characteristics			
Author/Year	STS*	Logistic EuroSCORE[a]	LVEF (%)*	AVA (cm^2)*	Mean Gradient (mm Hg)	Peak Gradient (mm Hg)	Valve Type	Valve Size (mm)†	Transfemoral, N (%)	ViV, N (%)
Arlt 2012[10]	NA	35 (25-48)	NA	NA	NA	NA	NA	NA	4 (100)	NA
Banjac 2016[11]	15.2 (6.96-62.82)	NA	35 (20-60)	NA	45±16	NA	SAPIEN: 10	29 (1), 26 (6), 23 (3)	8 (80)	NA
Dolmatova 2017[12]	9.4±6.6	NA	39±24.5	0.55±0.15	38.4±4.5	NA	SAPIEN: 5 CoreValve: 1	NA	5 (83.3)	1 (16.7)
Husser 2013[13]	NA	26 (18-41)	>50%: 6 (33) 35% to 50%: 5 (29) ≤35%: 7 (39)	0.8±1.0	43±10	74±15	NA	NA	12 (66.7)	NA
Pontailler 2017[14]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Seco 2014[15]	NA	51.73±24.95	38.75±17.52	0.64±0.11	39.7±7.66	59.8±14.14	NA	NA	11 (100)	1 (9)
Shreenivas 2015[8]	NA	NA	NA	NA	NA	NA	SAPIEN: 109	NA	NA	NA
Trenkwalder 2017[16]	NA	21.5±14.3	52.5±13.5	NA	50±16.8	NA	NA	NA	22 (66.7)	6 (18.2)
Uehara 2017[17]	12.2±6.2	NA	53.1±21.3	0.44±0.19	62.6±24.3	NA	SAPIEN: 7	23 (5), 26 (2)	1 (14.3)	NA

AVA indicates aortic valve area; EuroSCORE, European System for Cardiac Operative Risk Evaluation; LVEF, left ventricular ejection fraction; NA, not available; STS, Society of Thoracic Surgery; TAVR, transcatheter aortic valve replacement; ViV, valve-in-valve.

*Represented as mean±standard deviation or median (interquartile range).

†Represented as size in mm (number of patients).

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Table 3. Procedural Characteristics, Complications and Outcomes of CPB/VA-ECMO

	Procedural Characteristics				Complications					
Author/Year	CPB/VA-ECMO	Prophylactic, N (%)	Peripheral, N (%)	Duration (min)*	Major Bleed, N (%)	Vascular, N (%)	Tamponade, N (%)	CVA, N (%)	Hemodialysis, N (%)	Mortality, N (%)
Arlt 2012[10]	VA-ECMO	2 (50)	4 (100)	1 hour (3), 6 days (1)	0	0	NA	NA	NA	1 (25)
Banjac 2016[11]	VA-ECMO	0	8 (80)	87 (16-8514)	1 (10)	NA	1 (10)	1 (10)	NA	3 (30)
Dolmatova 2017[12]	VA-ECMO	1 (16.7)	6 (100)	94 (20 to 4 days)	3 (50)	3 (50)	3 (50)		NA	2 (33.3)
Husser 2013[13]	VA-ECMO	9 (50)	18 (100)	102 (87-148)† 116 (64-125)‡	6 (33)	5 (28)	3 (16)	2 (11)	3 (17)	4 (22)
Pontailler 2017[14]	VA-ECMO	NA	NA	NA	NA	NA	NA	NA	NA	2 (40)
Seco 2014[15]	VA-ECMO	8 (72.7)	11 (100)	NA	1 (9)	2 (18)	1 (9)	0		1 (9)
Shreenivas 2015[8]	CPB	NA	NA	NA	NA	NA	NA	NA	NA	58 (53.5)
Trenkwalder 2017[16]	VA-ECMO	0	33 (100)	114 (61-445)	27 (81.8)	8 (24.2)	NA	3 (9.1)	10 (30.3)	15 (45.5)§ 19 (57.6)‖
Uehara 2017[17]	VA-ECMO	3 (42.8)	6 (85.7)	51.8±29.9	1 (3)	0	NA	0	1 (14)	0 (0)§ 1 (14.2)‖

CPB indicates cardiopulmonary bypass; CVA, cerebrovascular accident; NA, not available; VA-ECMO, venoarterial extracorporeal membrane oxygenation.
*Mean±SD or median (interquartile range).
†Prophylactic.
‡Emergency.
§In-hospital/30-d mortality.
‖One-year mortality.

risk populations.[19] However, in patients presenting with concomitant cardiogenic shock, TAVR is associated with nearly 33% 30-day and 60% 1-year mortality.[20] As noted in a recent study from the Transcatheter Valve Therapy registry, nearly 10% of contemporary TAVRs are urgent or emergent and nearly 8% are performed in patients with LV ejection fraction <30%.[4] It is therefore of the utmost importance to optimize the hemodynamics in these patients to prevent periprocedural complications. Such patients may receive lower-support MCS devices such as the intra-aortic balloon pump and Impella; however some cases ultimately require escalation to the VA-ECMO due to persistent hemodynamic compromise.[7,21] In a study from the National Inpatient Sample, Singh et al noted 7.4% of TAVR procedures performed in 2011-2012 required VA-ECMO support that is likely reflective of early experience and learning curve associated with TAVR.[21]

Intra- or postprocedurally, CPB/VA-ECMO was used as an emergent maneuver with a variable incidence of 33% to 83% as noted in a majority of the studies in this systematic review. Mechanical complications such as LV or aortic annular rupture, obstruction of the left main coronary artery, and physiological complications such as rapid hemodynamic deterioration, severe aortic regurgitation, and cardiac arrest from ventricular tachycardia or fibrillation were the chief indications for CPB/VA-ECMO. Need for high-dose vasopressors, hemorrhagic shock, periprocedural myocardial infarction, and aortic dissection were quoted as other indications for CPB/VA-ECMO in this population. The relative advantages of VA-ECMO include rapid bedside access, high-flow circuit, relatively low expense, and concomitant pulmonary support that make it an attractive option in postoperative emergencies.[11] Importantly, unlike the percutaneous LV assist devices, the peripheral VA-ECMO does not require transseptal placement or the crossing of the aortic valve.[13] Cardiac tamponade, particularly from the rupture of a highly calcified and fragile aortic annulus, is an independent predictor of mortality in patients with TAVR.[22] The CPB/VA-ECMO has been noted to be extremely efficient in establishing rapid circulatory support in the treatment of cardiac tamponade in patients with complications of catheter-based interventions.[12] Access for VA-ECMO can either be obtained before TAVR procedure or emergently intraprocedurally. Cannulation is performed carefully in the femoral artery and femoral vein using ultrasound-guided technique, stiff 0.035 inch wires, and serial dilation to the desired VA-ECMO cannula size (typically 16F-18F arterial and 21F venous). If ECMO is required emergently during TAVR, large bore arterial access is usually already available, and the TAVR access sheath can be replaced with the ECMO arterial cannula. Venous access is often already available as it is used for temporary pacing.

Despite its stated benefits, CPB/VA-ECMO does have an inherent risk of complications. It is associated with significant need for blood transfusions either due to hemorrhage or hemolysis.[23] Transfusion, independently, in patients with VA-ECMO and TAVR has been associated with worse outcomes and needs to be carefully titrated against the need to maintain a robust cardiac output.[23,24] The need for large-bore femoral arterial cannulation is associated with a higher risk of vascular complications, such as retroperitoneal hemorrhage, distal limb ischemia, and arterial laceration.[25] Importantly, the use of either CPB or VA-ECMO has not shown convincing evidence of mortality advantage in patients undergoing TAVR. In a retrospective review of the PARTNER registry, Shreenivas et al demonstrated that, regardless of an emergent versus planned strategy, CPB was associated with nearly 2-fold higher mortality.[8] The Society of Thoracic Surgeons Predicted Risk of Mortality and Logistic European System for Cardiac Operative Risk Evaluation Scores have shown poor calibration for predicting MCS use, and have advocated for further research into optimal patient, procedural, and device factors to develop individualized risk scores.[8] Neurological complications in TAVR have been receiving increasing attention in recent years due to their long-term consequences. The use of emergent VA-ECMO in patients with TAVR has been associated with a higher rate of major strokes and necessitates further study into mechanistic aspects.[13]

In patients with severe LV dysfunction, acute heart failure, and cardiogenic shock, TAVR remains an attractive option to treat severe aortic stenosis, however only after clinical stabilization.[26] Currently, there is limited evidence on the prophylactic use of VA-ECMO in critically ill patients needing a TAVR procedure. As noted in this article, only 1 out of 9 studies defined a high-risk cohort for preprocedural VA-ECMO use.[15] Patients with pulmonary hypertension and biventricular failure would conceivably benefit from prophylactic VA-ECMO; however this high-risk cohort needs to be better defined to optimize the clinical outcomes.[17] We recommend a multidisciplinary team approach for the care of these patients to decide among available therapies including medical management, use of balloon aortic valvuloplasty, durable LV assist devices, and palliative care.[26] Ideally, these teams should comprise physicians from cardiology, interventional cardiology, cardiac surgery, critical care medicine, heart failure, palliative medicine, and anesthesiology.[26,27] It is important to incorporate input from palliative medicine physicians to balance the need for using sophisticated MCS devices against the use of futile, resource-intensive therapies that may be unlikely to improve clinical outcomes.

Limitations

This systematic review included only 9 studies, most of which were published in 2017. Heterogeneous study inclusion and exclusion criteria, high confounding from periprocedural

complications, and inconsistent criteria for the use of CPB/VA-ECMO prevented a meta-analysis on these data. Most of the included studies restricted their mortality outcomes to <30 days; therefore, there are limited data on the prediction of long-term outcomes in this population. It is conceivable that the timing from patient collapse to cannulation for cardiopulmonary support and the location of placement (operating room versus catheterization laboratory) have prognostic implications in patients needing CPB/VA-ECMO intraoperatively; however these data were inconsistently reported across studies preventing meaningful conclusions in this review. Higher hospital volumes for TAVR and VA-ECMO have independently been shown to be associated with better outcomes; however these data were not analyzed in this study, thereby limiting the assessment of clinical outcomes.[28,29]

Conclusions

In this systematic review, CPB/VA-ECMO was used in 4% in the early experience of patients undergoing TAVR, most commonly for periprocedural complications. There are limited data on preprocedural planned use of VA-ECMO, and the characteristics of this population remain poorly defined. In patients with cardiogenic shock, biventricular failure, and cardiopulmonary compromise, the use of VA-ECMO provides an attractive option for hemodynamic support. Further dedicated studies are needed to balance the need for using sophisticated MCS devices against the use of futile, resource-intensive therapies that may be unlikely to improve clinical outcomes in this high-risk population.

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Author Contributions

Study design, literature review, data analysis, and statistical analysis were done by Saraschandra V., H.S., H.P., and Saarwaani V.; data management, data analysis, and drafting of the manuscript were by Saraschandra V., H.S., H.P., and Saarwaani V.; access to data were by Saraschandra V., H.S., H.P., Saarwaani V., G.W.B., S.M.D., K.L.G., D.R.H., and M.F.E.; manuscript revision, intellectual revisions, and mentorship were done by G.W.B., S.M.D., K.L.G., D.R.H., and M.F.E.; and final approval was given by Saraschandra V., H.S., H.P., Saarwaani V., G.W.B., S.M.D., K.L.G., D.R.H., and M.F.E.

Disclosures

None.

References

1. Leon MB, Smith CR, Mack M, Miller DC, Moses JW, Svensson LG, Tuzcu EM, Webb JG, Fontana GP, Makkar RR, Brown DL, Block PC, Guyton RA, Pichard AD, Bavaria JE, Herrmann HC, Douglas PS, Petersen JL, Akin JJ, Anderson WN, Wang D, Pocock S. Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. *N Engl J Med*. 2010;363:1597–1607.
2. Leon MB, Smith CR, Mack MJ, Makkar RR, Svensson LG, Kodali SK, Thourani VH, Tuzcu EM, Miller DC, Herrmann HC, Doshi D, Cohen DJ, Pichard AD, Kapadia S, Dewey T, Babaliaros V, Szeto WY, Williams MR, Kereiakes D, Zajarias A, Greason KL, Whisenant BK, Hodson RW, Moses JW, Trento A, Brown DL, Fearon WF, Pibarot P, Hahn RT, Jaber WA, Anderson WN, Alu MC, Webb JG. Transcatheter or surgical aortic-valve replacement in intermediate-risk patients. *N Engl J Med*. 2016;374:1609–1620.
3. Thourani VH, Kodali S, Makkar RR, Herrmann HC, Williams M, Babaliaros V, Smalling R, Lim S, Malaisrie SC, Kapadia S, Szeto WY, Greason KL, Kereiakes D, Ailawadi G, Whisenant BK, Devireddy C, Leipsic J, Hahn RT, Pibarot P, Weissman NJ, Jaber WA, Cohen DJ, Suri R, Tuzcu EM, Svensson LG, Webb JG, Moses JW, Mack MJ, Miller DC, Smith CR, Alu MC, Parvataneni R, D'Agostino RB Jr, Leon MB. Transcatheter aortic valve replacement versus surgical valve replacement in intermediate-risk patients: a propensity score analysis. *Lancet*. 2016;387:2218–2225.
4. Holmes DR Jr, Nishimura RA, Grover FL, Brindis RG, Carroll JD, Edwards FH, Peterson ED, Rumsfeld JS, Shahian DM, Thourani VH, Tuzcu EM, Vemulapalli S, Hewitt K, Michaels J, Fitzgerald S, Mack MJ. Annual outcomes with transcatheter valve therapy: from the STS/ACC TVT registry. *Ann Thorac Surg*. 2016;101:789–800.
5. Chen CY, Tsai J, Hsu TY, Lai WY, Chen WK, Muo CH, Kao CH. ECMO used in a refractory ventricular tachycardia and ventricular fibrillation patient: a national case-control study. *Medicine (Baltimore)*. 2016;95:e3204.
6. Yannopoulos D, Bartos JA, Raveendran G, Conterato M, Frascone RJ, Trembley A, John R, Connett J, Benditt DG, Lurie KG, Wilson RF, Aufderheide TP. Coronary artery disease in patients with out-of-hospital refractory ventricular fibrillation cardiac arrest. *J Am Coll Cardiol*. 2017;70:1109–1117.
7. Singh V, Damluji AA, Mendirichaga R, Alfonso CE, Martinez CA, Williams D, Heldman AW, de Marchena EJ, O'Neill WW, Cohen MG. Elective or emergency use of mechanical circulatory support devices during transcatheter aortic valve replacement. *J Interv Cardiol*. 2016;29:513–522.
8. Shreenivas SS, Lilly SM, Szeto WY, Desai N, Anwaruddin S, Bavaria JE, Hudock KM, Thourani VH, Makkar R, Pichard A, Webb J, Dewey T, Kapadia S, Suri RM, Xu K, Leon MB, Herrmann HC. Cardiopulmonary bypass and intra-aortic balloon pump use is associated with higher short and long term mortality after transcatheter aortic valve replacement: a PARTNER trial substudy. *Catheter Cardiovasc Interv*. 2015;86:316–322.
9. Vandenbroucke JP, von Elm E, Altman DG, Gotzsche PC, Mulrow CD, Pocock SJ, Poole C, Schlesselman JJ, Egger M. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): explanation and elaboration. *PLoS Med*. 2007;4:e297.
10. Arlt M, Philipp A, Voelkel S, Schopka S, Husser O, Hengstenberg C, Schmid C, Hilker M. Early experiences with miniaturized extracorporeal life-support in the catheterization laboratory. *Eur J Cardiothorac Surg*. 2012;42:858–863.
11. Banjac I, Petrovic M, Akay MH, Janowiak LM, Radovancevic R, Nathan S, Patel M, Loyalka P, Kar B, Gregoric ID. Extracorporeal membrane oxygenation as a procedural rescue strategy for transcatheter aortic valve replacement cardiac complications. *ASAIO J*. 2016;62:e1–e4.
12. Dolmatova E, Moazzami K, Cocke TP, Elmann E, Vaidya P, Ng AF, Satya K, Narayan RL. Extracorporeal membrane oxygenation in transcatheter aortic valve replacement. *Asian Cardiovasc Thorac Ann*. 2017;25:31–34.
13. Husser O, Holzamer A, Philipp A, Nunez J, Bodi V, Muller T, Lubnow M, Luchner A, Lunz D, Riegger GA, Schmid C, Hengstenberg C, Hilker M. Emergency and prophylactic use of miniaturized veno-arterial extracorporeal membrane oxygenation in transcatheter aortic valve implantation. *Catheter Cardiovasc Interv*. 2013;82:E542–E551.
14. Pontailler M, Demondion P, Lebreton G, Golmard JL, Leprince P. Experience with extracorporeal life support for cardiogenic shock in the older population more than 70 years of age. *ASAIO J*. 2017;63:279–284.
15. Seco M, Forrest P, Jackson SA, Martinez G, Andvik S, Bannon PG, Ng M, Fraser JF, Wilson MK, Vallely MP. Extracorporeal membrane oxygenation for very high-risk transcatheter aortic valve implantation. *Heart Lung Circ*. 2014;23:957–962.
16. Trenkwalder T, Pellegrini C, Holzamer A, Philipp A, Rheude T, Michel J, Reinhard W, Joner M, Kasel AM, Kastrati A, Schunkert H, Endemann D, Debl K, Mayr NP, Hilker M, Hengstenberg C, Husser O. Emergency extracorporeal membrane oxygenation in transcatheter aortic valve implantation: a two-center experience of incidence, outcome and temporal trends from 2010 to 2015. *Catheter Cardiovasc Interv*. 2017. Available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/ccd.27385. Accessed July 2, 2018.

17. Uehara K, Minakata K, Saito N, Imai M, Daijo H, Nakatsu T, Sakamoto K, Yamazaki K, Kimura T, Sakata R. Use of extracorporeal membrane oxygenation in complicated transcatheter aortic valve replacement. *Gen Thorac Cardiovasc Surg*. 2017;65:329–336.
18. Afilalo J, Lauck S, Kim DH, Lefevre T, Piazza N, Lachapelle K, Martucci G, Lamy A, Labinaz M, Peterson MD, Arora RC, Noiseux N, Rassi A, Palacios IF, Genereux P, Lindman BR, Asgar AW, Kim CA, Trnkus A, Morais JA, Langlois Y, Rudski LG, Morin JF, Popma JJ, Webb JG, Perrault LP. Frailty in older adults undergoing aortic valve replacement: the FRAILTY-AVR study. *J Am Coll Cardiol*. 2017;70:689–700.
19. Toutouzas K, Synetos A, Latsios G, Mastrokostopoulos A, Stathogiannis K, Drakopoulou M, Trantalis G, Tsiamis E, Tousoulis D. The requirement of extracorporeal circulation system for transluminal aortic valve replacement: do we really need it in the catheterization laboratory? *Catheter Cardiovasc Interv*. 2018;91:E43–E48.
20. Frerker C, Schewel J, Schluter M, Schewel D, Ramadan H, Schmidt T, Thielsen T, Kreidel F, Schlingloff F, Bader R, Wohlmuth P, Schafer U, Kuck KH. Emergency transcatheter aortic valve replacement in patients with cardiogenic shock due to acutely decompensated aortic stenosis. *EuroIntervention*. 2016;11:1530–1536.
21. Singh V, Patel SV, Savani C, Patel NJ, Patel N, Arora S, Panaich SS, Deshmukh A, Cleman M, Mangi A, Forrest JK, Badheka AO. Mechanical circulatory support devices and transcatheter aortic valve implantation (from the National Inpatient Sample). *Am J Cardiol*. 2015;116:1574–1580.
22. Walther T, Hamm CW, Schuler G, Berkowitsch A, Kotting J, Mangner N, Mudra H, Beckmann A, Cremer J, Welz A, Lange R, Kuck KH, Mohr FW, Mollmann H. Perioperative results and complications in 15,964 transcatheter aortic valve replacements: prospective data from the GARY registry. *J Am Coll Cardiol*. 2015;65:2173–2180.
23. Smith A, Hardison D, Bridges B, Pietsch J. Red blood cell transfusion volume and mortality among patients receiving extracorporeal membrane oxygenation. *Perfusion*. 2013;28:54–60.
24. Seiffert M, Conradi L, Terstesse AC, Koschyk D, Schirmer J, Schnabel RB, Wilde S, Ojeda FM, Reichenspurner H, Blankenberg S, Schafer U, Treede H, Diemert P. Blood transfusion is associated with impaired outcome after transcatheter aortic valve implantation. *Catheter Cardiovasc Interv*. 2015;85:460–467.
25. Tanaka D, Hirose H, Cavarocchi N, Entwistle JW. The impact of vascular complications on survival of patients on venoarterial extracorporeal membrane oxygenation. *Ann Thorac Surg*. 2016;101:1729–1734.
26. Holmes DR Jr, Mack MJ, Kaul S, Agnihotri A, Alexander KP, Bailey SR, Calhoon JH, Carabello BA, Desai MY, Edwards FH, Francis GS, Gardner TJ, Kappetein AP, Linderbaum JA, Mukherjee C, Mukherjee D, Otto CM, Ruiz CE, Sacco RL, Smith D, Thomas JD, Harrington RA, Bhatt DL, Ferrari VA, Fisher JD, Garcia MJ, Gardner TJ, Gentile F, Gilson MF, Hernandez AF, Jacobs AK, Kaul S, Linderbaum JA, Moliterno DJ, Weitz HH. 2012 ACCF/AATS/SCAI/STS expert consensus document on transcatheter aortic valve replacement: developed in collaboration with the American Heart Association, American Society of Echocardiography, European Association for Cardio-Thoracic Surgery, Heart Failure Society of America, Mended Hearts, Society of Cardiovascular Anesthesiologists, Society of Cardiovascular Computed Tomography, and Society for Cardiovascular Magnetic Resonance. *Catheter Cardiovasc Interv*. 2012;79:1023–1082.
27. Lindman BR, Alexander KP, O'Gara PT, Afilalo J. Futility, benefit, and transcatheter aortic valve replacement. *JACC Cardiovasc Interv*. 2014;7:707–716.
28. Barbaro RP, Odetola FO, Kidwell KM, Paden ML, Bartlett RH, Davis MM, Annich GM. Association of hospital-level volume of extracorporeal membrane oxygenation cases and mortality. Analysis of the extracorporeal life support organization registry. *Am J Respir Crit Care Med*. 2015;191:894–901.
29. Khera S, Kolte D, Gupta T, Goldsweig A, Velagapudi P, Kalra A, Tang GHL, Aronow WS, Fonarow GC, Bhatt DL, Aronow HD, Kleiman NS, Reardon M, Gordon PC, Sharaf B, Abbott JD. Association between hospital volume and 30-day readmissions following transcatheter aortic valve replacement. *JAMA Cardiol*. 2017;2:732–741.

SUPPLEMENTAL MATERIAL

Data S1. Detailed search strategy.

Ovid MEDLINE(R) Epub Ahead of Print, In-Process & Other Non-Indexed Citations, Ovid MEDLINE(R) Daily and Ovid MEDLINE(R) <1946 to Present>

Search history sorted by search number ascending			
#	**Searches**	**Results**	**Type**
1	Transcatheter Aortic Valve Replacement/	2185	Advanced
2	(transcatheter adj2 (aorta or aortic)).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	6677	Advanced
3	(tavr or tavi).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	4648	Advanced
4	Heart Valve Prosthesis Implantation/	18789	Advanced
5	((heart valve prosthesis/ or 4) and aortic valve stenosis/) or ((cardiogenic shock.mp. or shock, cardiogenic/) and postoperative*.mp.) [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	9633	Advanced
6	or/1-3,5	13845	Advanced
7	(ecmo or vaecmo or vvecmo or ecls or els or ecpr).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	7604	Advanced
8	((veno arterial or venoarterial) adj3 (ecmo or extracorporeal)).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	1148	Advanced
9	Extracorporeal Membrane Oxygenation/	7849	Advanced
10	7 or 8 or 9	11364	Advanced
11	6 and 10	155	

Embase <1988 to 2018 Week 07>

Search history sorted by search number ascending			
#	**Searches**	**Results**	**Type**
1	Transcatheter Aortic Valve Replacement/	12812	Advanced
2	(transcatheter adj2 (aorta or aortic)).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word]	15507	Advanced
3	(tavr or tavi).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word]	11032	Advanced
4	Heart Valve Prosthesis Implantation/	9697	Advanced
5	((heart valve prosthesis/ or 4) and aortic valve stenosis/) or ((cardiogenic shock.mp. or shock, cardiogenic/) and postoperative*.mp.) [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word]	2244	Advanced
6	or/1-3,5	18194	Advanced
7	(ecmo or vaecmo or vvecmo or ecls or els or ecpr).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word]	13861	Advanced
8	((veno arterial or venoarterial) adj3 (ecmo or extracorporeal)).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word]	1919	Advanced
9	Extracorporeal Membrane Oxygenation/	16536	Advanced
10	7 or 8 or 9	22537	Advanced
11	6 and 10	416	

WoS

TOPIC: ((tavi OR tavr OR "transcathether aortic" OR "trans catheter aortic")) *AND* **TOPIC:** (ecmo OR extracorporeal OR "extra corporeal" OR vaecmo) 41

Scopus

(TITLE-ABS-KEY (tavi OR tavr OR "transcatheter aortic" OR "trans catheter aortic") AND TITLE-ABS-KEY (ecmo OR vaecmo OR extracorporeal* OR "extra corporeal*")) 128

Table S1. New-Castle Ottawa Scale for assessment of bias.

Author/ Year	Selection				Comparability	Outcome		
	Representativeness	Selection	Ascertainment	Outcome	Comparability	Assessment	Follow-up	Adequacy of follow-up
Arlt 2012[1]	*		*	*		*	*	*
Banjac 2016[2]	*		*	*		*	*	*
Dolmatova 2017[3]	*		*	*		*	*	*
Husser 2013[4]	*	*	*	*	*	*	*	*
Pontailler 2017[5]	*	*	*	*	*	*	*	*
Seco 2014[6]	*	*	*	*	**	*	*	*
Shreenivas 2015[7]	*		*	*	**	*	*	*
Trenkwalder 2017[8]	*		*	*		*	*	*
Uehara 2017[9]	*	*	*	*	*	*	*	*

Supplemental References:

1. Arlt M, Philipp A, Voelkel S, Schopka S, Husser O, Hengstenberg C, Schmid C and Hilker M. Early experiences with miniaturized extracorporeal life-support in the catheterization laboratory. *Eur J Cardiothorac Surg*. 2012;42:858-63.
2. Banjac I, Petrovic M, Akay MH, Janowiak LM, Radovancevic R, Nathan S, Patel M, Loyalka P, Kar B and Gregoric ID. Extracorporeal Membrane oxygenation as a procedural rescue strategy for transcatheter aortic valve replacement cardiac complications. *ASAIO J*. 2016;62:e1-4.
3. Dolmatova E, Moazzami K, Cocke TP, Elmann E, Vaidya P, Ng AF, Satya K and Narayan RL. Extracorporeal membrane oxygenation in transcatheter aortic valve replacement. *Asian Cardiovasc Thorac Ann*. 2017;25:31-34.
4. Husser O, Holzamer A, Philipp A, Nunez J, Bodi V, Muller T, Lubnow M, Luchner A, Lunz D, Riegger GA, Schmid C, Hengstenberg C and Hilker M. Emergency and prophylactic use of miniaturized veno-arterial extracorporeal membrane oxygenation in transcatheter aortic valve implantation. *Catheter Cardiovasc Interv*. 2013;82:E542-51.
5. Pontailler M, Demondion P, Lebreton G, Golmard JL and Leprince P. Experience with extracorporeal life support for cardiogenic shock in the older population more than 70 years of age. *ASAIO J*. 2017;63:279-284.
6. Seco M, Forrest P, Jackson SA, Martinez G, Andvik S, Bannon PG, Ng M, Fraser JF, Wilson MK and Vallely MP. Extracorporeal membrane oxygenation for very high-risk transcatheter aortic valve implantation. *Heart Lung Circ*. 2014;23:957-62.
7. Shreenivas SS, Lilly SM, Szeto WY, Desai N, Anwaruddin S, Bavaria JE, Hudock KM, Thourani VH, Makkar R, Pichard A, Webb J, Dewey T, Kapadia S, Suri RM, Xu K, Leon MB and Herrmann HC. Cardiopulmonary bypass and intra-aortic balloon pump use is associated with higher short and long term mortality after transcatheter aortic valve replacement: a PARTNER trial substudy. *Catheter Cardiovasc Interv*. 2015;86:316-22.
8. Trenkwalder T, Pellegrini C, Holzamer A, Philipp A, Rheude T, Michel J, Reinhard W, Joner M, Kasel AM, Kastrati A, Schunkert H, Endemann D, Debl K, Mayr NP, Hilker M, Hengstenberg C and Husser O. Emergency extracorporeal membrane oxygenation in transcatheter aortic valve implantation: A two-center experience of incidence, outcome and temporal trends from 2010 to 2015. *Catheter Cardiovasc Interv*. 2017; doi: 10.1002/ccd.27385. [Epub ahead of print].
9. Uehara K, Minakata K, Saito N, Imai M, Daijo H, Nakatsu T, Sakamoto K, Yamazaki K, Kimura T and Sakata R. Use of extracorporeal membrane oxygenation in complicated transcatheter aortic valve replacement. *Gen Thorac Cardiovasc Surg*. 2017;65:329-336.

Periprocedural Cardiopulmonary Bypass or Venoarterial Extracorporeal Membrane Oxygenation During Transcatheter Aortic Valve Replacement: A Systematic Review

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