Percutaneous Left Atrial Decompression in Patients Supported With Extracorporeal Membrane Oxygenation for Cardiac Disease*

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Objectives: Left atrial decompression using cardiac catheterization techniques has been described at centers with extracorporeal membrane oxygenation programs. Left atrial decompression can decrease cardiogenic edema, minimize ventricular distension, and allow myocardial recovery. We describe Boston Children's Hospital's experience with percutaneous left atrial decompression techniques, acute outcomes, and clinical impact of left atrial decompression in extracorporeal membrane oxygenation patients.

Subjects: Patients supported with extracorporeal membrane oxygenation undergoing percutaneous left atrial decompression were identified and assigned to two groups 1) myocarditis/suspected myocarditis or 2) nonmyocarditis cardiac disease.

Interventions: Three techniques including vent placement, static balloon dilation, and stent implantation were used.

Measurements and Main Results: Change in left atrial pressure and severity of pulmonary edema on chest radiography pre and post procedure, impact of timing and technique of left atrial decompression on resolution of left atrial hypertension, and extracorporeal membrane oxygenation survival were evaluated. Furthermore, we evaluated the presence of residual atrial septal defect during follow-up. Percutaneous left atrial decompression was performed in 44 of 419 extracorporeal membrane oxygenation cases (10.5%) and was frequently used for myocarditis (22 of 44 patients; 50%). Techniques included 25 vents, 17 static balloon dilations, and two stents. All techniques were equally successful and significantly reduced left atrial pressure and pulmonary edema. Survival to hospital discharge was not associated with extracorporeal membrane oxygenation duration prior to left atrial decompression, change in left atrial pressure, or technique used. Persistent atrial septal defect was noted in five surviving patients (excluding transplant recipients and deceased), two required closure.

Conclusions: Left atrial decompression can be performed effectively in children on extracorporeal membrane oxygenation using various percutaneous techniques. Reduction in pulmonary venous congestion is usually evident by chest radiography within 48 hours of intervention. Persistent atrial septal defect may require closure at the time of extracorporeal membrane oxygenation decannulation or during long-term follow-up. (*Pediatr Crit Care Med* 2015; 16:59–65)

Key Words: cardiac catheterization; congenital cardiac disease; extracorporeal membrane oxygenator; left atrial decompression; myocarditis

Extracorporeal membrane oxygenation (ECMO) is commonly used to support neonates and pediatric patients with cardiorespiratory dysfunction unresponsive to conventional therapies (1–3). ECMO plays an important role in supporting postoperative myocardial dysfunction in patients with congenital heart disease as well as myocardial dysfunction in those with acquired heart diseases such as myocarditis (4, 5). In the setting of ECMO support for left heart failure, left atrial (LA) decompression using catheter techniques has been described and pursued at many centers with active ECMO programs (6–11). The goals of left heart decompression for patients on ECMO are to decrease cardiogenic edema, pulmonary hemorrhage, and left ventricular (LV) distension and to allow myocardial recovery.

Prior studies have not investigated the impact of percutaneous LA decompression on outcomes in ECMO patients

*See also p. 85.

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(6–8, 12–15). Based on current literature, it is unknown whether any particular transcatheter techniques of left heart decompression are superior or whether the timing of intervention has an impact on patient survival. Analysis has been complicated by the use of multiple techniques and their varying degrees of efficacy.

The purpose of this study was to describe and compare techniques, adequacy, and impact of timing of LA decompression on patient outcomes in a group of pediatric patients supported with venoarterial ECMO (VA-ECMO) for cardiac failure.

MATERIALS AND METHODS

Approval to conduct a retrospective review of patient information and health records was obtained from the Committee on Clinical Investigation of the Boston Children's Hospital.

Patients

The cardiology departmental ECMO database was reviewed to identify patients who were supported with VA-ECMO and required percutaneous left heart decompression during the study period (January 2000 to December 2011). Cardiac diagnoses and clinical status at the time of initiation of ECMO (progressive cardiogenic shock vs active cardiopulmonary resuscitation [CPR]) were noted. Study subjects were categorized into two cohorts: 1) myocarditis or suspected myocarditis and 2) nonmyocarditis cardiac disease. Diagnosis of myocarditis/suspected myocarditis was by histological confirmation of the presence of any inflammatory cell infiltrates, edema, myocyte damage, or fibrosis. In patients without histology samples, myocarditis was diagnosed based on clinical presentation, absence of previous diagnosis of cardiac disease, and supporting investigations.

ECMO

All study subjects were supported with VA-ECMO. Arterial and venous cannulation sites, cannulation technique, and cannula size were at the discretion of the cardiothoracic surgeon. Decision to perform percutaneous LA decompression was made by the team of physicians managing the patient. A combination of baseline or worsening echocardiographic evidence of left heart dilation, chest radiography (CXR), and clinical signs of cardiogenic pulmonary edema or hemorrhage were used to aid in decision making.

Record Review

Data collection included a history of previous cardiac surgery and catheterization procedures or surgery immediately prior to the initiation of ECMO. Total time on ECMO was calculated from the database and exact timing of LA decompression obtained from catheterization report logs. Decompression time was designated as "the time the definitive intervention was performed on the atrial septum." Catheterization data collected included sites of access, saturations, hemodynamic data pre and post procedure, and specific equipment used to perform decompression.

Techniques of LA Decompression

All decompression procedures included were performed using percutaneous femoral venous access. The location (bedside or catheterization laboratory) and technique of LA decompression was at the discretion of the interventional cardiologist. Three types of procedures were performed: 1) insertion of a venting cannula into LA, 2) static balloon dilation of the atrial septum, or 3) implantation of a balloon expandable stent across the atrial septum. An existing atrial septal defect (ASD) was crossed when present, if not, transseptal puncture was performed. Informed consent was obtained for all procedures.

LA Vent Insertion. Venting of the LA was achieved using a number of different techniques and various catheters/cannula. These included standard perfusion cannula, long sheaths, end-hole catheters, and pericardiocentesis pigtail catheters. The cannula/sheath/catheter size chosen was guided by patient weight and efficacy of atrial decompression. Venting cannula was connected to the venous limb of the ECMO circuit and secured in position at the vascular access site.

Static Balloon Dilation. Static balloon dilation was performed using various over-the-wire angioplasty balloons, typically with incremental increase in balloon diameter. The balloon size was increased based on hemodynamic assessments of the effectiveness of decompression. Balloon type and size were also influenced by the limitations of vascular access and sheath size. Low-pressure (< 8 atmospheric pressure), moderate-pressure (≥ 8–14 atmospheric pressure), and high-pressure (≥ 15 atmospheric pressure) balloons were used based on the compliance and response of septal tissue to dilation. Cutting balloons were used if there was persistent resistance to dilation.

Stent Implantation. Patency of the atrial communication was maintained by implantation of a balloon-expandable, bare metal stent in patients in whom static balloon dilation was ineffective or anatomical/physiological factors determined the need for a stent to maintain LA decompression.

Outcome Measures and Data Analysis

Primary outcomes were the changes in LA pressure and degree of pulmonary congestion on CXR pre and post decompression. Patients with a fall in LA pressure greater than or equal to 2 mm Hg were considered a responder to the therapy. The extent of radiographic change was used as a clinical guide to the effectiveness of left heart decompression. A score was developed to quantify pulmonary congestion on CXR and assigned as follows: 0 = no evidence of pulmonary edema; 1 = mild perihilar or interstitial infiltrates, no evidence of pleural effusion; 2 = moderate perihilar or interstitial infiltrates, with or without pleural effusion; 3 = severe perihilar and interstitial infiltrates, with pleural effusions; and 4 = complete opacification of bilateral lung fields. Scoring was performed on the CXR immediately prior to LA decompression and after 48 hours postdecompression. For patients who died within 48 hours after decompression, CXR postprocedure and prior to death was used. Two study investigators (R.R.T., L.J.E.) independently scored radiographs to quantify severity of pulmonary edema. Disagreement in scores between reviewers was resolved by consensus. An improvement in CXR score was defined as a decrease in CXR score of less than or equal to 1. Other data collected included information on transition from ECMO to

a ventricular assist device (VAD) and survival to hospital discharge with or without cardiac transplantation (orthotopic heart transplantation [OHT]). The presence of a residual ASD at the time of VAD implantation, OHT, or on the most recent follow-up imaging (echocardiography or MRI) was recorded, and any procedure to close such a residual defect was noted.

Unless otherwise specified, data are presented as median (minimum-maximum) or frequency (%). Paired pre-/postdecompression data were compared using Wilcoxon signed rank test. Categorical and continuous outcomes were compared between groups using Wilcoxon rank-sum test and Fisher exact test, respectively.

RESULTS

Patients

A total of 419 ECMO runs were performed in 373 cardiac patients between January 2000 and December 2011. Overall survival to discharge for all patients requiring mechanical support during the study period was 49% (184 of 373). Surgically inserted vents were used during 39 ECMO runs (35 patients), with 20 (57%) surviving to discharge. Percutaneous left heart decompression was used in 44 ECMO runs (11%) in 43 patients who comprise the study population. One patient had two instances of LA vent placement. The first was during initial ECMO support for cardiogenic shock for dilated cardiomyopathy (DCM). This patient subsequently underwent OHT and presented 6 months posttransplant with severe graft failure due to rejection, suffered a cardiac arrest, and was resuscitated using ECMO. The patient received a second percutaneous LA vent in this context.

Demographic and ECMO data for each study group are summarized in **Table 1**. All patients were cannulated via the neck or femoral vessels. Myocarditis or suspected myocarditis was present in 22 patients (50%). Lymphocytic cell infiltrates were noted in 17 patients with varying degrees of edema, fibrosis, and myocyte hypertrophy/damage. In three patients, no mononuclear cell infiltrates were seen, but fibrosis, edema, or myocyte damage was noted. In the remaining two subjects, no histology was obtained and a diagnosis of suspected myocarditis was by clinical presentation and echo findings. Among the 22 patients with nonmyocarditis cardiac disease, nine had repaired congenital anomalies, three had undergone prior OHT, three had an arrhythmia-induced cardiomyopathy or cardiac arrest, and two had a restrictive cardiomyopathy. The remaining five patients had miscellaneous conditions resulting in LV failure: Kawasaki disease, lymphoma, hemophagocytic syndrome, cardiac arrest in the setting of an intramural coronary, and DCM in a patient with hemophilia.

TABLE 1. Demographic and Extracorporeal Membrane Oxygenation–Related Variables

Patient Data	Myocarditis	Nonmyocarditis
Patient demographics		
No. of patients	22	22
Gender (male:female)	12:10	12:10
Weight (kg)	36 (3–124)	22.5 (7.8–81.5)
Body surface area (m^2)	0.98 (0.21–2.51)	1.35 (0.34–1.97)
Age at the time of ECMO (yr)	9.7 (0.24–24.5)	10.8 (0.02–22.0)
ECMO indication		
Cardiogenic shock	5	11
Cardiopulmonary resuscitation	17	11
Cannulation site		
Neck	8	4
Femoral	11	9
Neck/femoral	3	9
ECMO duration (hr)	226 (15–274)	74 (18–403)
ECMO pre-vent (hr)	23 (1–33)	4 (0–116)
Outcome		
Survived	9	12
Survived with orthotopic heart transplantation	7	3
Death	6	7

ECMO = extracorporeal membrane oxygenation.
Values represented as median (range).

No significant differences in age or weight were seen between the two patient groups or the type of intervention performed (**Table 2**). Time from initiation of ECMO to LA decompression did not differ between groups (myocarditis, 11.5 hr; nonmyocarditis, 16 hr; $p = 0.24$). Decompression of the left heart was performed in the immediate postoperative period in two patients: in one patient 2 days post mitral valve replacement and the other required ECMO immediately after right ventricle-to-pulmonary artery conduit revision. A history of remote cardiac surgery was present in 13 patients (all in the nonmyocarditis cardiac disease cohort), and prior cardiac catheterization procedures had been performed in 45% of the study population.

Techniques of Decompression

Of the 44 decompression procedures, 42 were performed in the catheterization laboratory and two were performed at the bedside in the cardiac ICU. A vent was placed in 25 patients (57%), static balloon dilation was performed in 17 (39%), and an atrial septal stent was implanted in two (4%). Most of the vent placements were performed prior to August 2007 (21 of 25), whereas static balloon dilation alone was the predominant procedure employed during August 2007 and December 2011 (17 of 21). The stent implantations were performed in 2002 and 2005.

A preexisting but restrictive ASD was present in three patients. Brockenbrough transseptal puncture was performed in 39 patients, one of whom also underwent blade-septostomy due to a previously patched atrial septum, and the stiff-end of a guide wire was used to puncture the septum in one patient.

LA Vent Placement

Among the 25 patients in whom a vent was placed to decompress the LA, a Bio-Medicus (Medtronic, Minneapolis, MN) cannula (15F or 19F, 50 cm length) was used in 17 patients, with three placed across the septum immediately after transseptal puncture and the remainder after predilation of the septum (balloon diameters, ≤ 10 mm). The majority of cannulas were 15F (15 of 17). The median weight was 35 kg (7.8–90 kg) and median height 137 cm (98–178 cm). In six patients, a long Mullins sheath (Cook, Bloomington, IN) was used as an effective LA vent (median sheath size, 9F; range, 6–12F). In the remaining two patients, a 4F Radiofocus Glidecath (Terumo Medical, Somerset, NJ) catheter (patient weight, 9.3 kg) and an 8.3F pericardiocentesis pigtail catheter (Cook) were used to decompress the LA (patient weight, 8.7 kg).

Static Balloon Dilation

Among the 17 patients in whom LA decompression was performed with static balloon septoplasty, a single ASD was created in 16 and a second defect was created in one patient in whom a 20-mm high-pressure balloon inflated across the first defect did not provide adequate decompression. The maximum balloon diameter ranged from 10 to 24 mm (median, 12 mm). The number of different balloon diameters used per procedure ranged from 1 to 4 (median, 2). A cutting balloon was used in three procedures. A 10-mm-diameter balloon was used in three patients (median, 8 kg; range, 3–46 kg), and balloon diameters greater than or equal to 12 mm were used in 14 patients, five of whom weighed less than 20 kg (median, 37.5 kg; range, 5.8–124 kg).

Atrial Septal Stent Placement

The atrial septum was stented in two patients. One patient had history of left atrioventricular valve stenosis in the setting of a complete atrioventricular canal defect. Because prolonged ECMO and OHT were anticipated, stenting was performed as the primary procedure. An 8 mm × 18 mm premounted Palmaz-Genesis (Cordis Corp., Johnson and Johnson Medical, Bridgewater, NJ) stent was implanted and postdilated with a 10-mm balloon. The other patient who received a stent had restrictive cardiomyopathy, and ECMO was instituted as a bridge to OHT. Despite multiple balloon dilations to a maximum balloon size of 12 mm, a significant atrial gradient remained. Placement of a 9 mm × 19 mm premounted Palmaz-Genesis stent across the atrial septum successfully decompressed the LA.

Procedural Outcome

There was no statistical difference ($p = 0.3$) in the time from initiation of ECMO to LA decompression between the three procedure groups. Perforation of the LA occurred in one patient; however, this did not require additional intervention. One patient experienced a brief run of supraventricular tachyarrhythmia and was treated with cardioversion. There were no catheterization-related deaths.

Hemodynamic Outcomes

The mean LA pressure prior to decompression was documented in 38 patients (86%) (median, 24; range, 10–61 mm Hg). After decompression, the LA pressure was measured in 22 patients (50%) and was significantly lower than before decompression values (median, 17; range, 5–38 mm Hg; $p = 0.002$ for paired

TABLE 2. Features of Patients in the Different Diagnostic and Therapeutic Groups

Patient Group	Age at the time of Extracorporeal Membrane Oxygenation	Weight (kg)
Myocarditis ($n = 22$)	10.8 yr (7 d to 16.8 yr)	36.0 (3–124)
Nonmyocarditis ($n = 22$)	10.5 yr (91 d to 24.5 yr)	22.5 (7.8–90)
Vent ($n = 25$)	10.9 yr (90 d to 24.5 yr)	35 (7.8–90)
Balloon dilation ($n = 17$)	12.2 yr (7 d to 18.9 yr)	35 (3–124)
Stent ($n = 2$)	3.8 yr (1.1–6.6 yr)	14.5 (9–20)

comparison of patients with both pre- and postdecompression data). There were 18 patients (82%) defined as responders (≥ 2 mm Hg fall in LA pressure) to the therapy (median, 8; range, 2–43 mm Hg). The majority of patients without postdecompression data had undergone placement of a vent (21 of 26). In patients where a change in LA pressure was measured, no difference was found between the three treatment groups ($p = 0.2$) (**Fig. 1*A***). The median duration of time on ECMO support prior to decompression was highest in the early study period (2000–2002), at 21 hours. Since 2003, the median time to decompression was 9 hours.

CXR Outcomes

A precatheterization CXR was available in 42 patients (96%), and a postcatheterization CXR was available in 43 patients (98%). The postintervention CXR reviewed was performed at a median of 62.8 hours after decompression (13.9–93.4 hr). Predecompression CXR scores were not significantly related to the initial LA pressure ($p = 0.8$) (**Fig. 1*B***) or the type of underlying disease ($p = 0.25$).

An improvement in CXR score after decompression ($p < 0.001$) was seen in 30 of 41 patients (73%) with both pre- and postcatheterization studies, whereas there was no improvement or worsening in 11 patients (27%). The median CXR score prior to decompression was 3 (range, 0–4) and postdecompression was 1 (range, 0–3). No significant difference was identified between the method of decompression or the timing of decompression and degree of improvement in CXR score. Five of the 11 patients (45%) whose CXR did not improve after LA decompression died before discharge compared with seven of the 30 (23%) in whom the CXR did improve. This difference did not reach statistical significance ($p = 0.24$). CXR findings improved after LA decompression in 81% of patients (17 of 21) who survived to discharge without a transplant, 75% (6 of 8) of those who received a transplant, and 58% (7 of 12) of those who died. There was agreement between the two readers with respect to the CXR scale for 72 of the 85 CXR studies (85%). An example of pre- and postdecompression CXR is shown in **Figure 2** with complete resolution of the pulmonary edema.

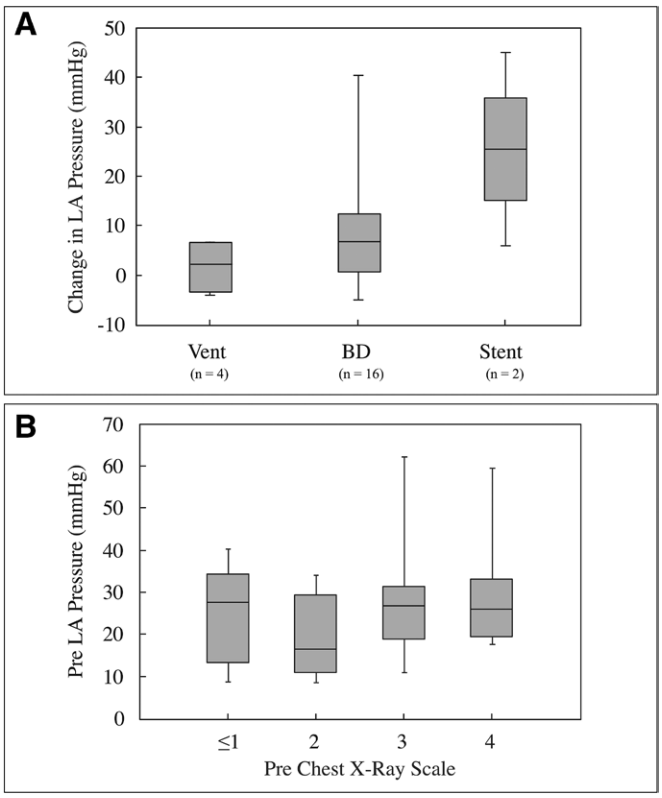

Figure 1. Hemodynamic variables compared to intervention type and precatheterization chest radiograph (CXR) score. **A**, *Box plots* depict the change in left atrial (LA) pressure after decompression (*boxes* represent the interquartile range and the *whiskers* depict the 10th and 90th percentiles) grouped according to treatment type. The number of patients in each treatment group is noted under each intervention. **B**, *Box plots* depict the predecompression LA pressure (*boxes* represent the interquartile range and the *whiskers* depict the 10th and 90th percentiles) grouped according to the precatheterization CXR score. BD = static balloon dilation.

Patient Outcomes

Overall, 31 patients (71%) survived after weaning off ECMO including 10 after OHT. No patients underwent revision or a repeat decompression procedure prior to decannulation from ECMO. Survival to hospital discharge (with or without OHT) was not associated with time from ECMO initiation to decompression procedure ($p = 0.2$), LA pressure prior to decompression ($p = 0.2$), change in LA pressure after decompression ($p = 0.1$), mode of presentation (cardiogenic shock vs CPR), or underlying disease (myocarditis vs nonmyocarditis cardiac disease, $p = 0.5$). **Figure 3** shows LA pressure and duration of ECMO prior to decompression for survivors and nonsurvivors.

Residual ASD

In the 31 patients surviving to hospital discharge, 10 underwent cardiac transplantation (four from ECMO, five on VAD, and one transplanted after decannulation from ECMO). Of the remaining 21 patients (11 vent, 10 balloon dilation), there were five (24%) with a persistent ASD.

A persistent ASD was found in two vent patients. One patient with a patched atrial septum who underwent LA decompression using blade septostomy required device closure of an atrial defect at 768 days following ECMO. The second patient had a trivial residual ASD shunt seen at most recent follow-up (584 d). In the balloon dilation group, one patient had the atrial communication closed by device at the time of ECMO decannulation. A small residual shunt was seen at last follow-up in one patient (199 d), and the remaining patient was lost to follow-up after discharge.

DISCUSSION

In this study, we reviewed the experience at the Boston Children's Hospital over a 12-year period in managing ECMO patients who underwent an invasive catheterization procedure to decompress the left heart during VA-ECMO.

Percutaneous left heart decompression was performed in approximately 10% of the patients managed with ECMO during the study period. We showed that LA decompression using

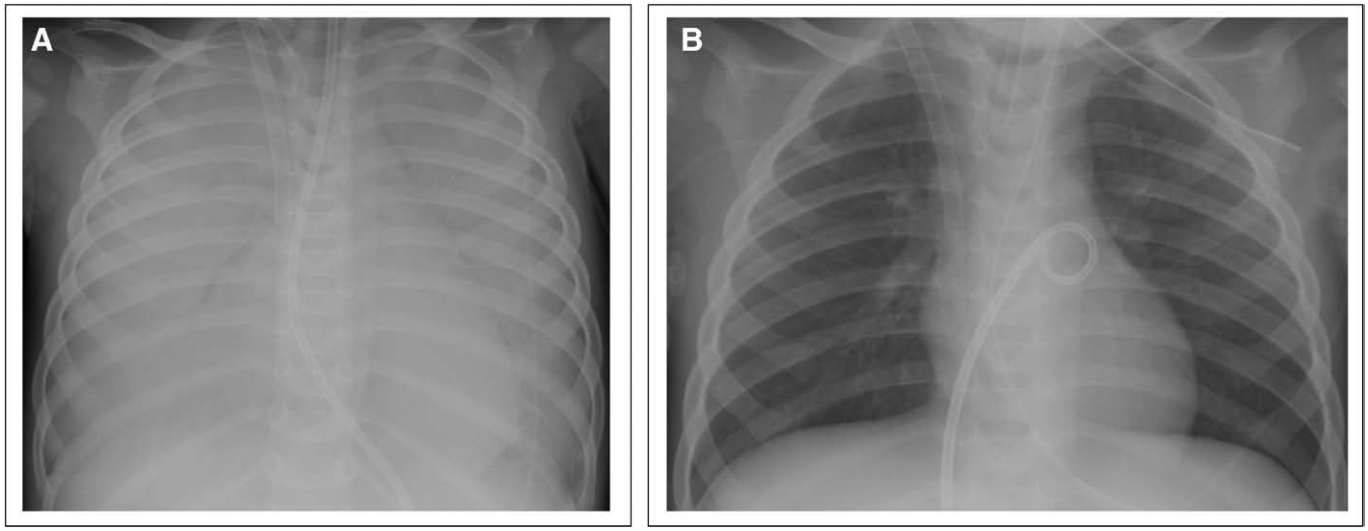

Figure 2. Frontal radiographs of the change in radiograph appearance after left atrial decompression. **A**, Prior to decompression, there is complete "white-out" of bilateral lung fields indicating severe (rating scale 4) pulmonary edema. **B**, The radiograph performed at 60 hr postdecompression shows an 8.3F pericardiocentesis pigtail catheter in the left atrium with complete resolution of the edema (scale 0).

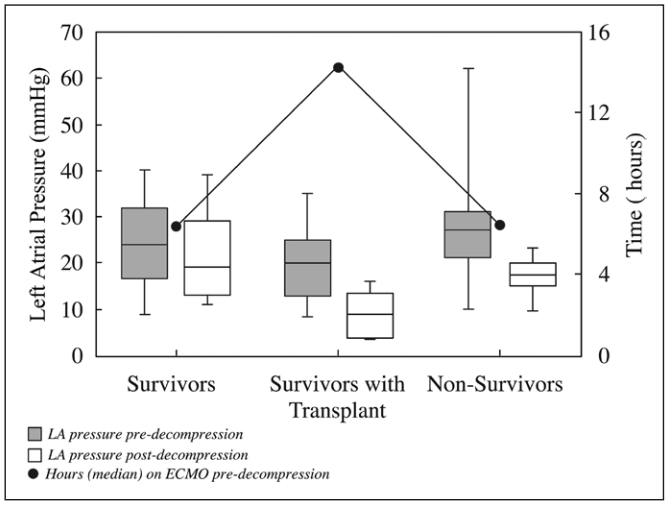

Figure 3. Left atrial (LA) pressure before and after catheterization compared between patient outcome groups. *Box plots* depict median LA pressure before and after LA decompression (*boxes* represent the interquartile range and *whiskers* depict the 10th and 90th percentiles) grouped according to patient outcome (survival, survival after orthotopic heart transplantation, and death). The *line* and *solid circles* depict the median duration on extracorporeal membrane oxygenation (ECMO) prior to decompression procedure for each of the outcome groups.

percutaneous cardiac catheterization–based techniques are effective, can be performed safely, and neither the timing of LA decompression after ECMO deployment nor the decompression technique used significantly influenced survival to hospital discharge.

Prolonged left heart distension leading to LA hypertension and subsequent pulmonary edema, hemorrhage, and failure has lead our institution to take a more aggressive approach to early decompression procedures to facilitate myocardial recovery and pulmonary protection. The recognition of these adverse effects was demonstrated by a substantial reduction in the median time to decompression for procedures performed after 2003.

All interventional procedures performed were successful in achieving the primary objective of decompressing the left heart. The need for Brockenbrough puncture to access the LA was performed safely with only one procedure complicated by LA perforation. A clear preference for vent insertion was noted between 2000 and 2007. More recently (2007–2011), static dilation of the septum alone using a combination of balloon types was the procedure of preference. A combination of clinical and technical experience has caused a shift in preference for balloon dilation alone. Early institutional experience with vents identified several technical issues related to management of the indwelling catheters: length of catheter (50 cm) in adult patients, kinking, poor flow, movement of the catheter with required patient care, and ongoing concern for thrombosis. The more recent trend toward use of lower profile, high-pressure balloons was equally effective in creating a suitable atrial defect for the duration of the patient's mechanical support without the need to add an additional limb to the support circuit.

A potential concern for balloon dilation, particularly with larger diameter balloons (up to 24 mm in this cohort), is the persistence of an atrial communication which could expose the patient to the long-term risks of right heart volume overload, embolic events, and need for potential reintervention to close the ASD. The presence of a residual ASD in survivors (excluding transplant recipients) was equivocal between the two predominant intervention types (vent and balloon dilation). A residual ASD was noted in 24% of these survivors (five patients), with two undergoing device closure, two with nonhemodynamically significant residual shunt, and one lost to follow-up. There was no increased risk for a persistent ASD with a static balloon compared to a percutaneous vent.

Stent implantation across the atrial septum carries a higher intrinsic procedural risk and postdecannulation, a significant residual shunt remains in those not undergoing OHT or open-heart surgery. In our limited cohort, no significant difference in LA pressure change (**Fig. 1*A***) or CXR improvement was noted

between the intervention types. Implantation of a stent may provide a more consistent and predictable degree of left heart decompression that can help decrease pulmonary congestion and maintain lung function in patients where ECMO is used as a bridge to VAD or OHT. Given the lack of clear benefit and higher procedural risk, stenting should be reserved for those patients who fail to adequately respond to static balloon dilation.

The correlation of LA hypertension with cardiogenic pulmonary edema has been well established (16, 17) with elevated LA pressures greater than 25 mm Hg causing fluid to breach the lung epithelium and cause flooding of the alveoli. The radiographic interpretation of CXR changes has also been reported (18, 19), with these studies suggesting 79–89% accuracy in the ability to distinguish cardiogenic from noncardiogenic edema. Even though we did not demonstrate a correlation between CXR score and preintervention LA pressure, CXR remains a useful tool in monitoring the clinical impact of LA decompression in ECMO patients. In our patient cohort, LA decompression led to a significant reduction in LA pressure and improvement in CXR score. Despite the reduction in LA pressure and improvement in CXR score, we did not observe a clear association with improved ECMO survival. Hospital mortality was higher in patients whose CXR did not improve after LA decompression compared with those in whom it did (45% vs 23%). Although this difference was not statistically significant, the analysis was likely underpowered to demonstrate a clinically relevant association. It is likely that multiple other factors such as severity of primary illness and ECMO complications have strongly influenced survival for our ECMO cohort.

LIMITATIONS

This study represents the 12-year experience from a single large referral center. The indications for ECMO support and subsequent timing of LA decompression procedure were performed on a case-by-case basis, without specific guidelines or treatment algorithms. Institutional and operator factors may have evolved over this time period. The study cohort had a broad range of cardiac conditions and diagnoses, which may have limited the ability to detect differences between patient groups. Specific limitations were encountered in the consistency and amount of hemodynamic information collected, particularly in the vent group prior to mid-2007. Given that the majority of vent procedures were performed in this time period, and the fact that postintervention LA pressure was not measured in the vent group, our ability to compare the different therapeutic strategies is limited.

CONCLUSIONS

Percutaneous decompression of the left heart can be performed effectively and safely in children on VA-ECMO using various techniques. Improvement in CXR appearance may help guide the effectiveness of the intervention. There were no significant differences in the LA decompression efficacy based on the three procedure types used. Although the number of patients with residual ASD that required intervention was small, long-term follow-up of ECMO patients managed with percutaneous LA decompression for residual ASD is essential.

REFERENCES

1. Haines NM, Rycus PT, Zwischenberger JB, et al: Extracorporeal Life Support Registry Report 2008: Neonatal and pediatric cardiac cases. *ASAIO J* 2009; 55:111–116
2. Kleinman ME, Chameides L, Schexnayder SM, et al: Part 14: Pediatric advanced life support: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation* 2010; 122:S876–S908
3. Thiagarajan RR, Laussen PC, Rycus PT, et al: Extracorporeal membrane oxygenation to aid cardiopulmonary resuscitation in infants and children. *Circulation* 2007; 116:1693–1700
4. Chai PJ, Jacobs JP, Dalton HJ, et al: Extracorporeal cardiopulmonary resuscitation for post-operative cardiac arrest: Indications, techniques, controversies, and early results–What is known (and unknown). *Cardiol Young* 2011; 21(Suppl 2):109–117
5. Wilmot I, Morales DL, Price JF, et al: Effectiveness of mechanical circulatory support in children with acute fulminant and persistent myocarditis. *J Card Fail* 2011; 17:487–494
6. Aiyagari RM, Rocchini AP, Remenapp RT, et al: Decompression of the left atrium during extracorporeal membrane oxygenation using a transseptal cannula incorporated into the circuit. *Crit Care Med* 2006; 34:2603–2606
7. Cheung MM, Goldman AP, Shekerdemian LS, et al: Percutaneous left ventricular "vent" insertion for left heart decompression during extracorporeal membrane oxygenation. *Pediatr Crit Care Med* 2003; 4:447–449
8. Seib PM, Faulkner SC, Erickson CC, et al: Blade and balloon atrial septostomy for left heart decompression in patients with severe ventricular dysfunction on extracorporeal membrane oxygenation. *Catheter Cardiovasc Interv* 1999; 46:179–186
9. Booth KL, Roth SJ, Perry SB, et al: Cardiac catheterization of patients supported by extracorporeal membrane oxygenation. *J Am Coll Cardiol* 2002; 40:1681–1686
10. desJardins SE, Crowley DC, Beekman RH, et al: Utility of cardiac catheterization in pediatric cardiac patients on ECMO. *Catheter Cardiovasc Interv* 1999; 46:62–67
11. Ettedgui J, Fricker FJ, Park SC, et al: Cardiac catheterization in children on extracorporeal membrane oxygenation. *Cardiol Young* 1996; 6:59–61
12. Swartz MF, Smith F, Byrum CJ, et al: Transseptal catheter decompression of the left ventricle during extracorporeal membrane oxygenation. *Pediatr Cardiol* 2012; 33:185–187
13. Fouilloux V, Lebrun L, Macé L, et al: Extracorporeal membranous oxygenation and left atrial decompression: A fast and minimally invasive approach. *Ann Thorac Surg* 2011; 91:1996–1997
14. Avalli L, Maggioni E, Sangalli F, et al: Percutaneous left-heart decompression during extracorporeal membrane oxygenation: An alternative to surgical and transeptal venting in adult patients. *ASAIO J* 2011; 57:38–40
15. Hlavacek AM, Atz AM, Bradley SM, et al: Left atrial decompression by percutaneous cannula placement while on extracorporeal membrane oxygenation. *J Thorac Cardiovasc Surg* 2005; 130:595–596
16. Staub NC: Pulmonary edema. *Physiol Rev* 1974; 54:678–811
17. Ware LB, Matthay MA: Clinical practice. Acute pulmonary edema. *N Engl J Med* 2005; 353:2788–2796
18. Milne EN, Pistolesi M, Miniati M, et al: The radiologic distinction of cardiogenic and noncardiogenic edema. *AJR Am J Roentgenol* 1985; 144:879–894
19. Thomason JW, Ely EW, Chiles C, et al: Appraising pulmonary edema using supine chest roentgenograms in ventilated patients. *Am J Respir Crit Care Med* 1998; 157:1600–1608