Extracorporeal cardiopulmonary resuscitation in adults and children: A review of literature, published guidelines and pediatric single-center program building experience

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Extracorporeal cardiopulmonary resuscitation (ECPR) is an adjunct supportive therapy to conventional cardiopulmonary resuscitation (CCPR) employing veno-arterial extracorporeal membrane oxygenation (VA-ECMO) in the setting of refractory cardiac arrest. Its use has seen a significant increase in the past decade, providing hope for good functional recovery to patients with cardiac arrest refractory to conventional resuscitation maneuvers. This review paper aims to summarize key findings from the ECPR literature available to date as well as the recommendations for ECPR set forth by leading national and international resuscitation societies. Additionally, we describe the successful pediatric ECPR program at Texas Children’s Hospital, highlighting the logistical, technical and educational features of the program.

KEYWORDS
ECMO—extracorporeal membrane oxygenation, ECPR program, ECPR training, extracorporeal resuscitation, pediatric ECPR, adult ECPR

Introduction

Extracorporeal cardiopulmonary resuscitation (ECPR) as an adjunct to conventional cardiopulmonary resuscitation (CCPR) employs veno-arterial extracorporeal membrane oxygenation (ECMO) in the setting of refractory cardiac arrest. CCPR provides 25–30% of normal cardiac output, while extracorporeal perfusion techniques provide optimized circulatory support and end organ perfusion (1–3). The utilization of ECPR has grown dramatically over the last two decades in both adult and pediatric populations (4–9). The Extracorporeal Life Support Organization (ELSO) is an international non-profit consortium of health care institutions, researchers, and industry partners that maintains a data registry of ECMO patients from more than 450 centers. More than 154,000 patients have been reported to ELSO, with ECPR cases representing 12% of ECMO cases.
Of the 18,000 ECPR cases, 12% are neonatal, 31% pediatric, and 57% adult, representing 5, 18, and 13% of all neonatal, pediatric, and adult ECMO cases respectively (4). The uptake and expansion of ECPR has been exponential, with fewer than 100 adult cases reported to ELSO per year before 2009 and more than 1,500 cases per year after 2018 (4).

ECPR is a resource-intensive resuscitation modality with logistical and technical challenges, availability limitations and an unclear economic impact. However, there is growing evidence suggesting potential benefit on patient outcomes. This review paper aims to summarize key findings from the ECPR literature available to date as well as the recommendations for ECPR set forth by national and international leading resuscitation societies. Additionally, we describe the successful pediatric ECPR program at Texas Children’s Hospital, highlighting the logistical, technical and educational features of the program.

Adult ECPR
Epidemiology

In the United States, the annual incidence of adult in-hospital cardiac arrests (IHCA) is an estimated 292,000 per year with 12–26% survival (10–15). Additionally, there are nearly 350,000 adult out-of-hospital cardiac arrests (OHCA) per year, accounting for one in five deaths in the United States (15–17). OHCA survival ranges from 8 to 15% and is influenced by a multitude of pre-hospital factors including arrest location, bystander presence, cardiopulmonary resuscitation (CPR) quality, etiology of cardiac arrest, initial cardiac rhythm, emergency medical services response time, time to defibrillation, time to return of spontaneous circulation (ROSC), as well as post-resuscitation care (11, 15, 17–25).

Despite advancements in resuscitation science, outcomes for adult IHCA and OHCA remain poor. Attempts to improve these outcomes, coupled with broadened availability and increased uptake of ECMO technology have resulted in the development of ECPR for refractory cardiac arrest. The use of ECPR is growing, with a tenfold increase from 2003 to 2014 and more than 10,000 adult ECPR cases reported to ELSO with a contemporary survival rate of 30% (4, 26).

Adult extracorporeal cardiopulmonary resuscitation

Naturally, the ECPR literature has investigated superiority over CCPR, including several meta-analyses as well as smaller, retrospective and prospective observational studies. Overall, these data support the use of ECPR, with largely positive reported effects on survival and neurologic outcome (27–35). For example, the meta-analysis by Ouweneel et al. (29) analyzed over 3,000 IHCA and OHCA patients receiving ECPR and CCPR and found an increase in 30-day survival and favorable neurologic outcome with ECPR, findings which were upheld on propensity analysis of over 400 patients, adjusting for likelihood of receiving ECPR. However, there are inherent challenges in comparing these modalities in a non-controlled manner with high risk of bias due to fundamental group differences in type of arrest and patient comorbidities, as well as potential for heterogeneity across studies. Study heterogeneity was cited as the primary reason precluding meta-analysis in the work performed by Holmberg et al. (36) for the International Liaison Committee on Resuscitation (ILCOR) 2019 consensus statement.

Despite its growing use, ECPR is employed in <1% of adult IHCA, with use influenced by patient age, comorbidities, cardiac diagnoses and time and location of arrest (37). ECPR for adult IHCA is investigated by multiple studies (6, 27, 30, 38–68). Meta-analyses reveal promising pooled survival rates ranging from 30 to 38%, with 84% of survivors achieving favorable neurologic outcome (7, 69). However, meta-analyses comparing ECPR to CCPR in IHCA alone demonstrate mixed results, with improved ECPR outcomes noted by Chen et al. (30) but no significant difference reported by Wang et al. (27).

As a result of evolving technology and deployment efficiency, ECPR is utilized more frequently in OHCA settings as well (31, 35, 48, 66, 67, 70–99). A recent, large retrospective study by Bougouin et al. (84) analyzed 13,000 cases of OHCA from 2011 to 2018 in the Paris region, with 4% of patients receiving ECPR, and demonstrated no survival benefit for ECPR (8%) compared to CCPR (9%). However, several single center prospective and retrospective studies demonstrated improved survival with ECPR up to 43% (48, 72, 82, 83, 88, 96, 97). Similarly, a recent meta-analysis by Downing et al. of 44 studies inclusive of 3,097 patients identified an ECPR survival rate of 24%, with 18% of all patients having a good neurological outcome, consistent with previous meta-analyses (31, 35).

Currently there are only two published randomized controlled trials directly comparing ECPR and CCPR for OHCA, the “Advanced reperfusion strategies for patients with out-of-hospital cardiac arrest and refractory ventricular fibrillation (ARREST)” trial and “Effect of Intra-arrest Transport, Extracorporeal Cardiopulmonary Resuscitation, and Immediate Invasive Assessment and Treatment on Functional Neurologic Outcome in Refractory Out-of-Hospital Cardiac Arrest: A Randomized Clinical Trial” (8, 9). As for the ARREST trial, the authors report 43% survival to hospital discharge in patients treated with ECPR compared to 7% with CCPR. After enrollment of only 30 patients, the study was terminated at the first interim analysis given that the posterior probability of ECMO superiority exceeded the prespecified monitoring boundary. Of note, all patients in the ARREST trial had an initial shockable rhythm and benefited from a streamlined process for ECPR initiation (8). The other randomized trial by Belohlavek
et al. evaluated 256 OHCA patients, including all presenting rhythms (ventricular fibrillation, asystole and pulseless electrical activity), and reported 32% survival with good neurological outcome at 180 days in the ECPR group compared to 22% in the CCPR group ($p = 0.09$) (9). Of note, the trial was stopped prematurely when prespecified criteria for futility were met, however, the authors note that the trial was possibly underpowered to detect a clinically relevant difference (9).

Available data suggest that ECPR survival and neurologic outcome are impacted by various clinical and patient specifics. Favorable predictors include age (43, 68, 99), IHCA (48, 51, 67, 100, 101), shockable rhythm (28, 55, 68, 78, 84, 97–99, 102, 103), temporary ROSC (68, 84, 104), witnessed arrest with bystander CPR (104), shorter CCPR duration or time from arrest to ECMO (28, 43, 51, 64, 67, 68, 83, 86, 87, 94, 96, 102–104), higher baseline pH (93, 98, 99, 102, 103), lower baseline lactate (51, 86, 98, 102, 103) and percutaneous coronary intervention (43, 48, 91, 102). Pre-hospital cannulation for OHCA ECPR may have additional benefits on survival and neurologic outcome by reducing low-flow time for patients with longer anticipated transport times (83, 84, 91, 95, 105).

In light of the available literature, leading national and international resuscitation societies have set forth guidelines on the use of ECPR in adults. Table 1 summarizes the recommendations from the American Heart Association (AHA), European Resuscitation Council (ERC), ILCOR (106, 108, 110), and ELSO (114, 115). Of note, ILCOR commissioned a systematic review of ECPR in 2018 which informed the published 2019 Consensus on Science with Treatment Recommendations (CoSTR) (36, 111, 112).

**ECPR candidacy**

ECPR patient selection is a crucial determination as it relates to ECPR program building as well as research trial design. Data that definitively identify the patients most likely to benefit from ECPR are still needed, and thus candidacy determinations will be ECPR center or trial dependent. In general, ECPR is thought to provide a bridge to process reversal (e.g., myocardial infarction requiring percutaneous coronary intervention), other definitive management (e.g., ventricular assist device or organ transplantation), or further information seeking (106, 108, 114). Informed, patient-tailored institutional decisions about ECPR candidacy should occur as early as possible (114). The 2021 ELSO Interim Guideline Consensus Statement on ECPR in adults proposes the following inclusion criteria: age <70 years, witnessed arrest, arrest to CPR time <5 min, initial rhythm ventricular fibrillation, ventricular tachycardia, or pulseless electrical activity, arrest to ECMO time <60 min, end tidal carbon dioxide >10 mmHg during CCPR prior to cannulation, intermittent ROSC or recurrent ventricular fibrillation, “signs of life” during CCPR, absence of greater than mild aortic valve incompetence, and absence of significant end-stage organ failures or comorbidities (114). However, the majority of contemporary ECPR programs do not have formalized inclusion and exclusion criteria (116).

**Post-ECPR care**

Mortality after ROSC can be at least partially attributed to the complex pathophysiologic state following cardiac arrest involving the initial ischemic insult as well as reperfusion and post-reperfusion injuries and their effect on organ systems, referred to as “post-cardiac arrest syndrome” (117). Post-resuscitation care is a resource-intensive multidisciplinary undertaking that requires critical monitoring and tailored management strategies to prevent additional injury, as well as investigation of the precipitating cause and reversal or treatment if necessary.

Recommendations for post-resuscitation care are set forth by AHA, informed most recently by an ILCOR 2020 systematic review and CoSTR for advanced life support (106, 110). These recommendations highlight avoidance of hypotension using crystalloid, inotropes, or mechanical support as needed (goal systolic blood pressure $\geq 90$ mmHg; mean arterial blood pressure $\geq 65$ mmHg), avoidance of hypoxemia and hyperoxemia (target oxygen saturation of 92–98%), and maintenance of normocapnia (arterial partial pressure of carbon dioxide 35–45 mmHg) (106, 110). Other components of care include maintenance of euglycemia and timely diagnosis and treatment of seizures. Prophylactic use of anti-seizure medications, antibiotics and steroids are not advised (106, 110). Lastly, while hyperthermia prevention and management are universally accepted, targeted temperature management (TTM) is an area of ongoing research and relative controversy. TTM was recommended between 32 and 36°C for at least 24 h for comatose adults following ROSC after IHCA or OHCA with any initial rhythm, based on landmark studies by Bernard et al. and Hypothermia after Cardiac Arrest Study Group (118, 119). However, a recent large, open-label trial comparing targeted hypothermia and normothermia found no difference in 6-month survival or functional outcome following OHCA (120). In light of this and other evidence, the ERC revised their guidelines on temperature control, advising continuous temperature monitoring and preventing fever ($>37.7^\circ$C) for 72 h, but there was insufficient evidence to recommend for or against temperature control at 32–36°C (121).

While additional data is needed to inform best practices for post-ECPR care, providers should consider general post-resuscitation care recommendations as well as the ELSO Interim Guideline Consensus Statement on ECPR in adults (114). After ECMO blood flow of 3–4 L/min is achieved, providers should target mean arterial blood pressure $\geq 60$ and $<80$ mmHg (114).
| Society | Adults | IHCA | Children | OHCA |
|---------|--------|------|----------|------|
| AHA     | “There is insufficient evidence to recommend the routine use of extracorporeal CPR (ECPR) for patients with cardiac arrest. ECPR may be considered for select cardiac arrest patients for whom the suspected cause of the cardiac arrest is potentially reversible during a limited period of mechanical circulatory support.” (106) |
|        | Class of recommendation: 2b Weak |
|        | Level of evidence: Limited Data (C-LD) |
| ERC    | “Consider extracorporeal CPR (eCPR) as a rescue therapy for selected patients with cardiac arrest when conventional ALS measures are failing or to facilitate specific interventions (e.g., coronary angiography and percutaneous coronary intervention (PCI), pulmonary thrombectomy for massive pulmonary embolism, rewarming after hypothermic cardiac arrest) in settings in which it can be implemented.” (108) |
| ILCOR  | “…ECPR may be considered as a rescue therapy for selected patients with cardiac arrest when conventional CPR is failing in settings in which it can be implemented (weak recommendation, very low-certainty evidence).” (110–112) |
| ELSO   | “We recommend that institutions offering ECPR develop a guideline for ECPR treatment which includes eligibility, goals of treatment, and a timeline with conditions for stopping ECMO in those without neurologic recovery, or in those ineligible for long-term mechanical cardiac support because of insufficient cardiac recovery.” (114) |
|        | “There is insufficient evidence in pediatric OHCA to formulate a treatment recommendation for the use of ECPR.” (111–113) |

IHCA, in-hospital cardiac arrest; OHCA, out-of-hospital cardiac arrest; AHA, American Heart Association; ERC, European Resuscitation Council; ILCOR, International Liaison Committee On Resuscitation; ELSO, Extracorporeal Life Support Organization; CPR, cardiopulmonary resuscitation; ECPR, extracorporeal cardiopulmonary resuscitation; ECMO, extracorporeal membrane oxygenation; ALS, advanced life support; ED, emergency department; ROSC, return of spontaneous circulation; PALS, pediatric advanced life support.
Unintended hyperoxia and hypocapnia should be avoided, as they have been associated with worse outcomes for patients receiving ECPR (122, 123). Prompt and frequent measurements of oxygenation and ventilation are needed, with adjustments to ECMO oxygen gas and sweep flow to target arterial oxygen saturation of 92–97% and normocarbia (114). With respect to temperature control, the circuit warmer can be programmed as desired, and early intervention for hyperthermia is similarly feasible using the circuit warmer and heat exchanger. Lastly, patients exhibiting signs of left ventricular hypertension and pulmonary edema should be considered for left ventricular unloading and/or venting (114).

**Pediatric ECPR**

**Epidemiology**

There are over 15,000 pediatric in-hospital cardiac arrests requiring CPR per year in the United States, with several studies documenting an increase in survival over time (10, 11, 124, 125). Pediatric IHCA occurs in 2–6% of intensive care admissions, and the majority of arrests occur in intensively monitored patients (90%) with a secured airway (80%) (11, 126–128). Survival rates for pediatric IHCA are 40–49% with 34–90% of survivors achieving favorable neurological outcome depending on the study (11, 15, 128, 129). Additionally, over 5,000 children experience non-traumatic OHCA annually (130). In contrast to adult OHCA, pediatric OHCA is more commonly attributed to non-cardiac etiologies (131). Survival rates are ~11–13%, with favorable neurological outcomes occurring in 85–90% of survivors (11, 15).

**Pediatric extracorporeal cardiopulmonary resuscitation**

Pediatric ECPR, like adult ECPR, aims to optimize cardiac output and end organ perfusion with the goal of improving arrest survivalability and neurological outcomes. The most recent ELSO Registry International Summary Report, comprising data from inception through 2020, identifies 5,682 pediatric ECPR cases (4). ECPR cases account for 18% of all pediatric ECMO cases, which has markedly increased from 5% in 2004 (4, 132). The survival rate to discharge for pediatric ECPR is 42% per the ELSO Registry, with over 70% of cases performed for an indication of cardiac disease (4, 133). Similarly, a recent systemic review and meta-analysis of 28 studies and 1,300 pediatric ECPR patients (excluding registry patients) demonstrated 30% survival with favorable neurological outcome (134). A secondary analysis of the IHCA “Therapeutic Hypothermia After Pediatric Cardiac Arrest” (THAPCA) trial demonstrated that ECPR survivors had similar long term neurobehavioral outcomes to other post-arrest survivors, with one third of ECPR patients alive with good functional status at 1 year (135, 136). Despite the steady growth of ECPR utilization over time in pediatric patients, the pediatric ECPR literature lacks randomized studies and the majority of data is focused on IHCA in cardiac patients (4, 5, 134, 137–149).

In a landmark paper, Lasa et al. performed a large systematic comparison of ECPR and CCPR for pediatric patients with IHCA requiring >10 min resuscitation using the Get With the Guidelines-Resuscitation Registry (GWTG-R), a large multicenter national registry. Their analysis demonstrated improved survival and survival with favorable neurological outcome for the ECPR group compared to the CCPR group even after adjusting for illness type, pre-existing conditions, and arrest features. Their findings were further confirmed on propensity score-matched analysis (150).

Analyses of the GWTG-R and the National Registry of Cardiopulmonary Resuscitation demonstrated use of ECPR in 3–7% of IHCA, with the most frequent utilization for cardiac surgical patients (150–153). In fact, ECPR was used in 27% of arrests between 2014 and 2016 according to the Pediatric Cardiac Critical Care Consortium registry (154). Use of ECPR for refractory IHCA has increased threefold in the last two decades according to the National Inpatient Sample dataset (128). Overall, registry analyses show ECPR survival is 27–44% for IHCA with neurologically favorable outcomes in 56–73% of survivors (150–152, 155). Several studies demonstrated improved ECPR survival (32–48%) for patients with cardiac disease compared to non-cardiac patients (151, 152, 156–159). A meta-analysis including 762 patients by Joffe et al. (155) described overall ECPR survival of 49%, with favorable neurological outcomes occurring in 79% of survivors and non-cardiac disease associated with increased risk of mortality. Other retrospective single, multicenter, and database studies describe 25–73% overall survival and 50–100% of survivors having good neurologic outcome (137, 145, 147, 149, 156, 159–176).

The literature is scarce regarding the use of ECPR for pediatric OHCA, which comprises only 3% of ECPR cases reported to ELSO (138). From 2010 to 2019, 33 patients (7 survivors) reported to ELSO experienced arrest during emergency medical services transport and received ECPR by the receiving institution (Bilodeau and McMullan, personal communication). ECPR in pediatric patients reported to ELSO Registry (Unpublished raw data). Additionally, ECPR for pediatric OHCA is described by infrequent single center reports (177, 178). Likewise, there is only one case report of out-of-hospital cannulation in a pediatric patient (179).

Aside from preexisting non-cardiac disease, patient factors associated with ECPR outcomes include pre-ECPR pH, lactate and renal injury as well as post-ECPR lactate and pH (133, 135, 146, 147, 149–151, 157–160, 163, 164, 168, 171–173, 175, 180, 181). In a secondary analysis of ECPR within the IHCA THAPCA trial, receipt of open-chest cardiac massage was associated with shorter CPR duration, survival and good
neurological outcome at 1 year, while open-chest cardiac massage is a negative predictor in other studies (135, 164). Increasing CPR interruptions during cannulation have been associated with worse outcomes (145). Additionally, several studies have described an association between CPR duration and survival (145, 147–149, 158, 160, 162, 164, 165, 168, 172, 174, 175). Meanwhile, other studies have not upheld this finding, and moreover, some authors have recognized the ability of ECPR to rescue patients with very prolonged arrest times such as 60–95 min (146, 156, 158, 166, 169–171, 180). Arrest rhythm has also been inconsistently associated with outcomes (124, 135, 149, 158, 182). Complications while on ECMO portend a worse prognosis (133, 157–159, 168, 171, 173).

In light of the available literature, leading national and international resuscitation societies have set forth guidelines on the use of ECPR in children. Table 1 summarizes the recommendations from AHA, ERC, ILCOR and ELSO (107, 109, 113, 115).

ECPR candidacy

Data are currently insufficient to definitively identify appropriate pediatric ECPR candidates. A recent survey of pediatric critical care physicians demonstrated that ECPR activation decisions are complex and heterogeneous, but most consistently influenced by patient diagnosis (cardiac vs. non-cardiac), CPR duration, arrest location, witnessed arrest, and blood pH (183). ECPR consideration is currently advised by AHA for patients with cardiac diagnoses when CCPR is failing, but should be reserved to experienced institutions (107). There are insufficient data to advise uniform application in other pediatric subgroups (107).

Post-ECPR care

Following the application of ECPR, optimal post-resuscitation care for children is critical. Post-cardiac arrest syndrome in children mimics that in adults, involving brain injury, myocardial dysfunction, systemic ischemia and reperfusion injury, and unresolved inciting pathology (184). AHA recommendations for pediatric post-resuscitation care include optimizing hemodynamics (systolic blood pressure >5th percentile for age) utilizing crystalloid and/or vasopressor agents as needed, targeting normoxemia (oxygen saturations 94–99%) and limiting exposure to severe hypocapnia or hypoxemia. Oxygenation and ventilation targets may be modified in the context of a patient’s underlying condition (107, 184). With respect to TTM following pediatric cardiac arrest, the AHA recommends continuous measurement of core temperature and targeting either normothermia (36–37.5 °C) for 5 days or hypothermia (32–34 °C) for 2 days followed by normothermia (36–37.5 °C) for 3 days (107, 184, 185). Evaluated robustly by the multicenter randomized controlled THAPCA study, TTM at 32–34 °C when compared to TTM at 36–37.5 °C had no effect on survival or neurologic outcome (136, 186). Additionally, hyperthermia is common, and if persistent, is associated with worse neurological outcomes and should therefore be aggressively treated (107, 184, 187).

While there is no literature specific to post-ECPR care in children, management should at minimum uphold the recommendations for general post-resuscitation care. As is true for adults upon ECPR initiation, ECMO circuit flows in conjunction with fluids and vasopressors should be titrated to optimize hemodynamics. Extracorporeal support has the potential to mitigate post-arrest hypotension which is common, and associated with worse outcomes (188). In addition, institution of extracorporeal support should prompt attention to oxygenation (risk of hyperoxia), ventilation and ECMO sweep gas flow (risk for hypocapnia), and desired temperature management (programmed temperature control with circuit warmer and heat exchanger).

Neonatal ECPR

There are 2,261 cases of neonatal ECPR reported to the ELSO Registry with an overall survival to discharge of 42% (4). Approximately half of ELSO neonatal ECMO centers report performing neonatal ECPR (189). Neonatal cases are included within GWTG-R studies, representing 21% of pediatric ECPR cases with 38% survival and 46% of survivors having favorable neurological outcome (150). Post-cardiotomy ECPR cases for neonates with congenital heart disease predominate (181, 190, 191). Additionally, neonates may require ECPR in the setting of respiratory disease, which carries a favorable prognosis (133). Other positive prognostic indicators identified by the literature include greater gestational age, weight, and cardiac arrhythmia causing arrest (190). Unfavorable factors include lower pre-ECPR arterial oxygenation, delayed lactate clearance, ECMO duration and complications (181, 190).

ECPR program building

ECPR is a complex multi-disciplinary resuscitation modality that involves substantial resources and strong institutional commitment. Successful ECPR programs require maintenance of expertise and equipment, as well as integrated quality improvement mechanisms to assess important program metrics (114).

A successful ECPR program has been established at Texas Children’s Hospital since 2005. Figure 1 details an example ECPR deployment algorithm. ECPR candidacy is discussed preemptively in high-risk patients. All cardiac patients are ECPR candidates, except for those with significant comorbidities.
or vascular access limitations. Certain non-cardiac patients are considered on a case-by-case basis, including but not limited to patients with pulmonary hypertension, drug overdose, and pulmonary embolism. Candidate patients experiencing a witnessed arrest in pre-defined locations may receive ECPR, including the emergency department (ED), intensive care units (ICU), cardiac catheterization lab, or operating room (OR). Activation can be triggered by either cardiac intensive care physician or congenital heart surgeon, when high-quality CPR fails to achieve sustainable ROSC after two cycles. A staff member calls in to the operator requesting ECPR activation and system page out, which notifies congenital heart surgeon, operating room staff, cardiovascular anesthesia, perfusionists, and pharmacy as to the patient location and weight. The congenital heart surgery attending and fellow are available on-call 24/7. During regular business hours, the team is in-house, however, after-hours, it is expected that they are within a 20-min distance from the hospital should ECPR activation be needed. The assisting operating room team, bedside team, and ECMO technical team are in-house 24/7 and would start preparing before the arrival of the surgical team. Each team member adheres to their protocol that includes equipment gathering. Bundled surgical cannulation carts and crystalloid-primed ECMO circuits are pre-prepared and maintained in key locations dedicated to rapid deployment. ECPR cannulation takes place in specific hospital locations including the OR, cardiac catheterization lab, or ICU. Thus, candidate patients experiencing arrest in the ED will be transported. The optimal ECPR cannulation strategy is dependent upon patient anatomy, size, operative status, and pathophysiology. For example, a post-sternotomy patient with open chest may be cannulated centrally given ease of access, while closed-chest, pre-operative, medical cardiac, or non-cardiac patients are more appropriate for initial peripheral cannulation.

Laussen and Guerguerian (192) review the critical components for establishing and sustaining an ECPR program. They describe four time intervals of importance: cardiac arrest to CCPR (interval 1), start of CCPR to ECPR activation (interval 2), ECPR activation to ECMO flow (interval 3), and ECMO flow to post-resuscitation care (interval 4). Interval 1 should not exceed 1 min in the event of witnessed IHCA. Interval 2 can be minimized by early ECPR activation by designated team members. Interval 3 may be reduced when ECPR occurs in familiar, well-controlled, protocol-driven environments. Many centers utilize preassigned roles, flowcharts and job aides to enhance staff preparedness and decrease deployment time (177, 191, 193–195). Protocolized, rapid response ECMO programs have proven successful in reducing neurologic complications in both ECPR and general ECMO patients (196).

A key quality initiative for our ECPR program is our clinical event debriefings conducted after all ECPR cases. Started in 2014, these debriefs aim to improve team dynamics and patients’ outcome. The structured approach investigates the teams’ clinical performance, resources, facilities, including process or system problems to improve. Table top simulations and live simulation based system testings are frequently used to optimize any identified paucities.
Team training and simulation

Simulation has been widely regarded as beneficial for ECMO team training, technical skills, provider confidence, communication and collaboration, improving deployment times and adherence to ECPR protocols (174, 191, 194, 195, 197–205). Moreover, simulation can be used to develop, test, and/or adapt an ECPR protocol (195, 198, 206).

At Texas Children’s Hospital, ECMO team members participate in a structured education and simulation program with competency benchmarks covering all aspects of ECMO delivery (Figure 2). A series of didactic sessions reviews basic fundamentals, including respiratory and cardiac pathophysiology potentially necessitating ECMO support. Didactics further explore ECMO candidacy, cannulation strategies and complications. Subsequently, providers engage in progressively complex wet lab trainings. Wet lab trainings reinforce important processes: setting up a dry circuit (<15 min), priming with crystalloid (<8 min), priming with blood (<5 min), and pump, oxygenator, and circuit exchanges. Wet lab exercises are repeated and timed until proficiency is demonstrated. Next, trainees transition to actively assisting other trained ECMO providers and are evaluated in that capacity. Direct feedback and debriefing sessions provide continuing education.

Multi-disciplinary ECPR simulation sessions are held regularly at Texas Children’s Hospital to enhance interprofessional team performance, communication, and technical skills. Scenarios reinforce key components of patient encounters, from deterioration and arrest through ECPR activation, patient transport, cannulation, and circuit management. Additionally, we utilize a surgical simulation model for ECMO cannulation (Image 1; RediStik™ ECMO Cannulation Trainer, Sawbones, Vashon, WA, USA). The model aims to improve procedural skills with ECMO neck cannulation, highly pertinent to ECPR deployment in pediatric patients. Alternate models have been employed by other ECPR simulation programs (199, 207).

Conclusion

ECPR has the potential to rescue selected patients when conventional resuscitation efforts are failing. There is growing evidence that ECPR improves survival and neurological outcomes in adult OHCA and IHCA. Further well-designed, randomized clinical trials are needed to identify the most appropriate ECPR candidates, as well as optimal pre-ECPR and post-ECPR practices. Additional research is needed to explore the utility of ECPR in pediatric and neonatal populations, with a focus on understanding the role in non-cardiac illness and OHCA. Effective application of ECPR requires substantial health care resources and strong institutional commitment. Institutions should develop a systematic approach, utilizing team training, simulations, and quality improvement mechanisms in order to establish a successful ECPR program.

Author contributions

PB, MA, and TO contributed to conception, design of the study, wrote the first draft of the manuscript, and edited...
the final draft to the manuscript submitted. PB, TO, MA, AS, and CB wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This work was funded by Michael Pickett MSN, APRN, PNP-BC and Texas Children’s Hospital Heart Center Innovation Award 2020, $5k.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmed.2022.935424/full#supplementary-material

SUPPLEMENTARY IMAGE 1

RediStik™ ECMO Cannulation Trainer. ECMO: extracorporeal membrane oxygenation [https://www.youtube.com/watch?v=UwCJNP94g3ObJlist=PLVWzmgauEkKcGfI9yV9wIFyTu3f11brindex=2].

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Supplementary material

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