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Clinical paper

Outcomes after extracorporeal cardiopulmonary resuscitation in pediatric in-hospital cardiac arrest: does quality of CPR matter?

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Abstract

Background: ECPR patients who receive guideline-compliant CPR will have improved survival to hospital discharge (SHD) compared to patients who do not receive guideline-compliant CPR, regardless of CPR duration.

Methods: Retrospective, observational study from PediRES-Q of IHCA in children (<18 years) requiring ECMO to achieve ROSC. We assessed compliance of 60-sec chest compression (CC) epochs according to 2020 AHA guideline targets. Guideline-compliant CPR defined as > 60% epochs meeting compliance criteria for each target. Differences assessed utilizing Fisher's exact tests. Logistic regression used to assess guideline compliance and SHD, controlling for age, arterial line, duration of CPR, and clustering by site.

Results: We analyzed 157 index ECPR events (> 5 epochs): 62 infants (<1 year), 52 children (1-<8 years), and 43 adolescents (8-≤18 years) with CPR quality metric data from 20 sites. Median CPR duration 54 mins (IQR 40,66), median weight 12.0 kgs (IQR 6.0,28.5), and 74/157 (47%) with a cardiac diagnosis. Guideline compliance was not significantly associated with SHD after adjusted logistic regression; however, overall compliance was poor across age groups: 0% in < 1 year, 4% in 1-<8 years and 10% in 8–18 years. Age and duration of CPR were significantly associated with SHD, as 8-<18 years had 64% lower odds of SHD than < 8 year (aOR = 0.36 {0.17, 0.76; $P = 0.007$) and every minute increase in duration of CPR decreased survival odds by 2% (aOR = 0.98 {0.96,1.0; $P = 0.02$).

Conclusion: While adherence to AHA guideline-complaint CPR was not significantly associated with SHD, patient age and CPR duration were significant predictors. These findings emphasize the need to better understand factors associated with survival after pediatric ECPR while also helping to drive improvements in ECPR care models.

Keywords: Cardiopulmonary resuscitation, Extracorporeal membrane oxygenation, Pediatric, In-hospital cardiac arrest, Survival

Introduction

It is estimated that ∼15,000 pediatric index in-hospital cardiac arrests (IHCA) occur each year in the United States.[1] Survival to hospital discharge occurs in about 22–52% of children and is impacted by multiple patient- and event-level factors including age of patient, illness category, duration and quality of cardiopulmonary resuscitation (CPR).[2–6] Extracorporeal cardiopulmonary resuscitation (ECPR) is an advanced rescue therapy, where an extracorporeal circuit is employed, to support circulation in patients with cardiac arrest refractory to conventional CPR.[7] A recent report of ECPR in children combined highly relevant cardiac arrest data with extracorporeal membrane oxygenation (ECMO) data, through linkage of two multicenter databases: the American Heart Association (AHA) Get With The Guidelines—Resuscitation (GWTG-R) and the Extracorporeal Life Support (ELSO) registries.[8] Mortality prior to hospital discharge was 59.4% with multivariable logistic regression models demonstrating that duration of cardiac arrest was associated with increased odds of death prior to hospital discharge. Additional ECPR studies suggest that the risk of mortality and of unfavorable neurologic outcomes among survivors increases with longer CPR duration.[9–11]

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Other studies, however, have shown no association or nonlinear association between longer CPR duration and unfavorable outcomes.[12–14] What is missing from these prior reports is data on CPR quality during the complex process of cannulating an infant or child onto ECMO. Perhaps what is more important for improved outcomes following ECPR is the quality of CPR provided, despite the duration of CPR, prior to ECMO cannulation.

We aim to describe differences in survival to hospital discharge (SHD) and neurologic outcomes following ECPR within patients ≤ 18 years of age from the Pediatric Resuscitation Quality (PediRES-Q) Collaborative. We hypothesize that ECPR patients with AHA guideline-compliant CPR (chest compression rate, depth, and fraction) during cannulation for ECMO will have improved SHD and SHD with favorable neurologic outcome compared to patients who do not receive guideline-complaint CPR, regardless of CPR duration.

Methods

This was a retrospective cohort study using data from the Pediatric Resuscitation Quality (pediRES-Q) Collaborative (ClinicalTrials.gov: NCT02708134), a large international multi-center network of children's hospitals that collects data on pediatric cardiac arrests and chest compression quality metrics. The study was approved by the Children's Hospital of Philadelphia IRB and each hospital's institutional review or research ethics board (Approval number 15–012099, under the study title "Quality of Pediatric Resuscitation in a Multicenter Collaborative: An Observational Study"). There was a waiver of consent per United States Code of Federal Regulations 45 CFR 46.116(d) and 45 CFR 46.408(a). Data use agreements were obtained for each institution and compliance with the Health Insurance Portability and Accountability Act (HIPAA) was maintained.

Cohort selection

This study included data from October 2015 to December 2023 on all pediatric IHCAs that required ECMO to achieve return of circulation (ROC) reported to the pediRES-Q registry. We included data on index (first in-hospital) ECPR events from all children ≥ 37 weeks' gestation and < 18 years of age who received external chest compressions (CC) with quality metric data recorded using the ZOLL R-series monitor-defibrillator (ZOLL Medical, Chelmsford, MA) and dual sensor defibrillator pads, placed on the anterior (chest) and posterior (back) of the patient. Accelerometer-based technology embedded in each pad recorded CC rate, depth and fraction and mitigated depth artifact caused by hospital mattress deflection during compressions.

We excluded patients with out-of-hospital cardiac arrest, including patients who arrived at the hospital receiving CPR. Patients were excluded if they were on ECMO at the beginning of the arrest, had prior ECMO, if there were limitations to CPR in place or had incomplete data collection (i.e., event within last month or patient not yet discharged), or did not have CPR metric data collected. Events were also excluded if they had < 33.3% CPR metric data captured, or sensors were placed > 10 min after the start of chest compressions. In analysis of CC epochs, we excluded compression values for accelerometer depths of < 1 cm or > 8 cm for children less than 8 years, and > 10 cm for children equal to or greater than 8 years of age, as this was likely artifact. Additionally, events with a single sensor pad, dual anterior-apical or incorrect sensor position documented were excluded from depth analysis.

For each IHCA event, we collected data on prospectively selected pre-arrest and intra-arrest factors. Pre-arrest characteristics included patient demographics, pre-existing conditions, illness category, cardiac arrest etiology, and interventions in place at the onset of IHCA. Intra-arrest data included CC quality [depth, rate and fraction], timing of arrest, presence of invasive monitoring prior to the onset of cardiac arrest (arterial line), initial rhythm, and CPR duration (defined as time from onset of chest compressions to ECMO initiation, in minutes).

Definition of cardiopulmonary resuscitation quality metrics

Epochs were defined as 60 s increments of CC metric data. We recorded compliance of each epoch and compared them to AHA 2020 guidelines for basic life support with the predefined targets of CC rate 100–120 per minute; CC depth ≥ 3.4 cm for < 1 year of age and ≥ 4.4 cm for 1 to < 8 years of age, and 4.5–6.6 cm for 8 to < 18 years of age; and chest compression fraction (CCF) ≥ 80%. Chest compression fraction refers to the percentage of time during a CPR event that CC were performed without interruption. Compliance for each event was defined as ≥ 60% of event epochs meeting these AHA guideline targets.

Outcome measures

Survival to hospital discharge was the primary outcome variable. Secondary outcomes included return of circulation (ROC) with ECMO (ECPR) and SHD with favorable neurological outcome (FNO). SHD and FNO are reported at the patient-level. ROC was defined as successful cannulation to ECMO during the cardiac arrest event. SHD with FNO was prospectively defined as a Pediatric Cerebral Performance Category (PCPC) score of 1, 2 at the time of discharge from the hospital, or no change from pre-arrest PCPC score. Unfavorable FNO was defined as a PCPC score of 3–6.

Statistical analysis

Demographic and clinical characteristics are presented as median/IQR (interquartile range) for continuous variables and percentages for categorical variables. For each event, we calculated CC quality metrics of median CC rate, CC depth, and CCF, as well as CC rate compliance, depth compliance, fraction compliance, and overall compliance. We then reported the CC quality metrics by age groups: < 1 year, 1-<8 years, and 8-<18 years. Comparison between patients with and without guideline-complaint CPR were analyzed by the Fisher's exact test. Multivariable logistic regressions with random site effect were used to assess the relationship between guideline-compliance and SHD adjusting for age group, presence of an indwelling arterial line at the start of the IHCA event, and CPR duration. Because of the sample size, exact conditional logistic regressions were used to assess the relationship between compliance and SHD with FNO. Statistical analyses were conducted using SAS 9.4 (SAS Institute, Raleigh, NC.

Results

Between 10/2015 and 12/2023 there were 157 index ECPR events (> 5 epochs) with 6869 60-sec epochs of CC metrics in 62 infants (<1 year), 52 children (1-<8 years), and 43 adolescents (8-≤ 18 years) from 20 participating sites (1–25 events per site, median

6, IQR [2–13]) in the pediRES-Q Collaborative (Fig. 1). Overall SHD was 57/157 (36%) and survival with FNO 40/152 (26%); neurologic outcome data was missing in 5 patients (3 in < 1 year, 1 in 1-<8years, and 1 in 8–18 years). Survival was highest in the < 1-year olds (47%), with the lowest SHD in the 8–18-year-olds (21%). Patient demographics and clinical characteristics are delineated in Table 1. Median age was 2.0 years (IQR 0.4,10.7), median weight 12.0 kgs (IQR 6.0,28.5), and 76/157 patients (48%) had a cardiac diagnosis with 28/157 (18%) with single ventricle anatomy. Median duration of CPR was 54 mins (IQR 40,66), 69% had a pulseless rhythm documented at the time CC were initiated, and over 80% of the cohort received > 5 doses of epinephrine. Physiologic monitoring was in place in 142 (90%) of the events with an indwelling arterial line in 66 (42%), central venous pressure in 41 (25%), end-tidal CO^2 in 155 (99%), and near-infrared spectroscopy monitoring cerebral oxygenation in 31 (20%). Physiologic monitoring was reported to have been used to guide CPR in 58 (37%) of the events, not used in 21 (13%), and unknown in 67 (43%).

Chest compression metrics of rate, depth, and CCF are described for the entire cohort and by individual age groups (<1 year, 1-<8 years, and 8–18 years) in Table 2. Chest compression rate compliance was the metric most closely followed according to current guidelines with rate compliance of 50%, 65%, and 72% in respective age groups (<1 year, 1-<8 years, and 8–18 years). Chest compression depth was the least compliant metric with 14%, 26%, and 27% in respective age groups (<1 year, 1-<8 years, and 8–18 years). CCF was 39%, 42%, and 51% in respective age groups (<1 year, 1-<8 years, and 8–18 years). CPR metric guideline compliance vs guideline non-compliance and SHD and SHD with FNO are depicted in Fig. 2A (<1 year), 2B (1-<8 years), and 2C (8–18 years). When chest compression metrics were combined to assess compliance (rate + depth, depth + CCF, rate + CCF), there was even less compliance with current guidelines, with overall compliance (rate + depth + CCF) very poor in all age groups: 0% in < 1 year, 4% in 1-<8 years and 10% in 8–18 years. Comparison between patients with and without guideline-complaint CPR are shown in Table 3. Most

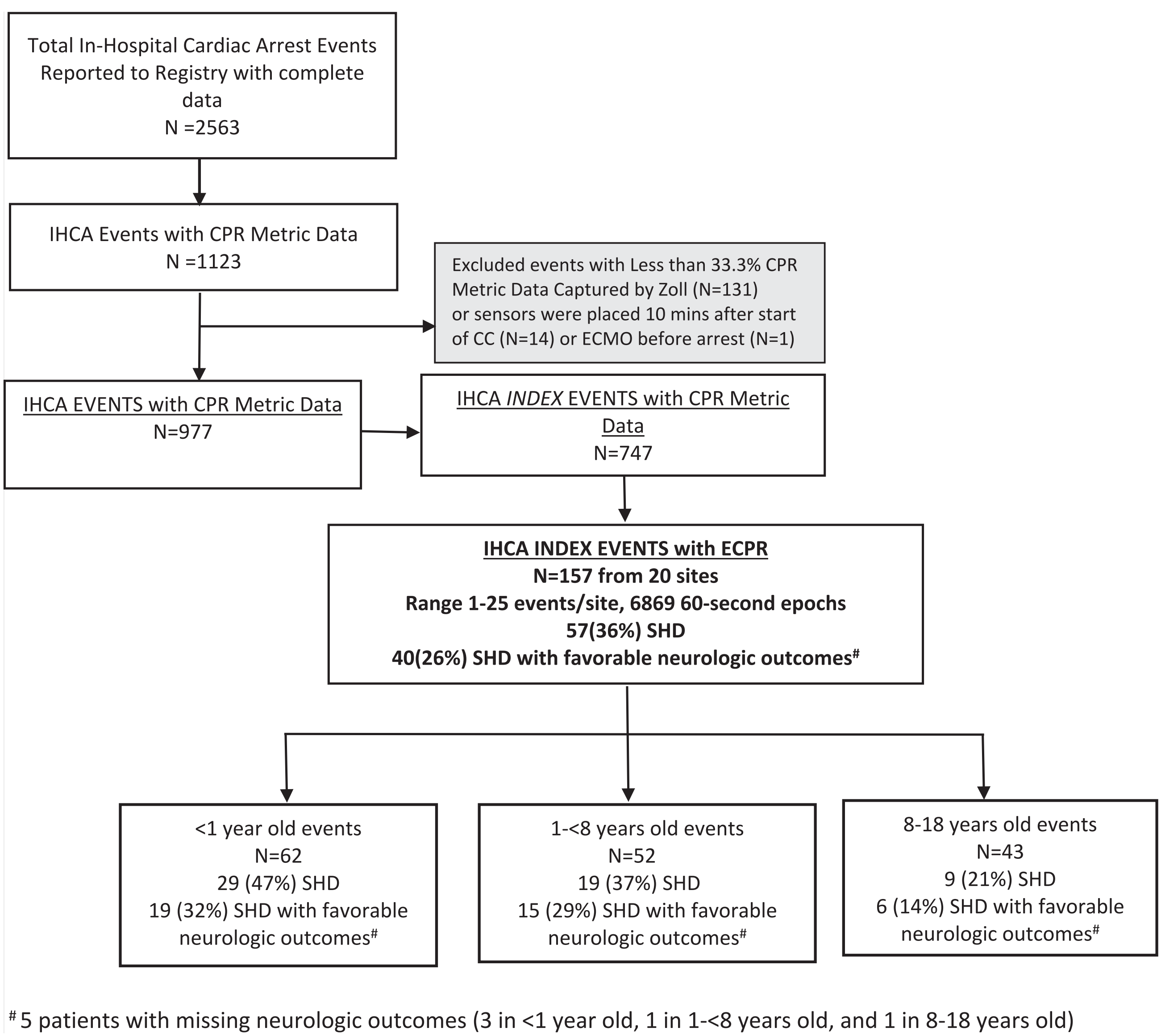

Fig. 1 – Utstein style consort diagram. # 5 patients with missing neurologic outcomes (3 in < 1 year old, 1 in 1-<8 years old, and 1 in 8–18 years old).

Table 1 – Clinical characteristics (Total Index Events N = 157).

Variables	*Descriptive Statistics*
Age at arrest, years (median, IQR)	2.0 (0.4,10.7)
Male (N, %)	90 (57)
Weight (median, IQR)	12.0 (6.0,28.5)
Pre-existing Conditions [may have > 1 reported at time of event] (N, %)	
Cardiac Malformation (N, %)	76 (48)
Single ventricle (N, %)	28 (18)
Congenital Malformation (Non-cardiac)	28 (18)
Hypotension/Hypoperfusion	58 (37)
Metabolic/Electrolyte Abnormality	35 (22)
Metastatic or Hematologic Malignancy	8 (5)
Renal insufficiency	15 (10)
Respiratory insufficiency	81 (52)
Septicemia	18 (11)
Immediate Cause of Arrest (N, %) [*Each Event can have > 1 cause listed*]	
Arrhythmia	42 (27)
Hypotension	64 (41)
Hypoxia/Respiratory decompensation	61 (39)
First Documented Rhythm at Time of Chest Compressions (N, %)	
Palpable Pulse	45 (29)
Pulseless	108 (69)
Unknown	4 (3)
Duration of CPR (median, IQR)	54 (40,66)
Number of 60-second epochs (median, IQR)	41 (27,55)
Time to first epi dose (median, IQR)	2.0 (0.0,3.5)
Shockable rhythm (N, %)	29 (18)
Illness category (N, %)	
Medical cardiac	51 (32)
Medical non-cardiac	50 (32)
Surgical cardiac	44 (28)
Surgical non-cardiac	11 (7)
Trauma	1 (1)
Intervention in place at time of first CCIV/IO continuous infusion of antiarrhythmics (N, %)	12 (8)
Antiarrhythmics administered during the CPR event (N, %)	31 (20)
Epinephrine Dose (N, %)	
None	2 (1)
1 dose only	5 (3)
2–4 dose	20 (13)
5 + dose	130 (83)
Atropine (N, %)	13 (8)
Calcium (N, %)	115 (73)
Fluid bolus (N, %)	61 (39)
Inhaled nitric oxide (N, %)	7 (4)
Magnesium Sulfate (N, %)	19 (12)
Other Vasopressors (N, %)	10 (6)
Sodium bicarbonate (N, %)	106 (8)
Vasopressin (N, %)	8 (5)
Other medicine (N, %)	86 (55)
Physiologic monitoring in place (N, %)	142 (90)
Arterial line	66 (42)
Central venous pressure	41 (25)
Near infra-red spectroscopy	31 (20)
End-tidal CO[2]	155 (99)
Physiologic monitoring used to guide CPR (N, %)	58 (37)
Physiologic monitoring not used to guide CPR (N, %)	21 (13)
Physiologic monitoring unknown if used to guide CPR (N, %)	67 (43)

notably there were no statistically significant differences in SHD or SHD with FNO based on compliance with any CC metric in any age group.

Multivariable logistic regression was used to assess the relationship between CC rate, depth, and fraction compliance with SHD (Table 4). After adjusting for age, presence of an indwelling arterial

Table 2 – CPR Characteristics and Outcomes by Age Groups.

CPR Metric Characteristics/Survival Outcomes	< 1 year (N = 62)	1-<8 years (N = 52)	8–18 years (N = 43)	Overall (N = 157)
CC rate (median (IQR))	119 (110,125)	114 (110,121)	112 (109,118)	114 (110,121)
CC depth (median (IQR))#	2.5 (2.1,3.3)	3.6 (3.0,4.7)	6.0 (4.9,6.7)	3.4 (2.5,4.8)
CCF (median (IQR))	81 (71,89)	84 (70,91)	88 (78,94)	83 (71,91)
Rate compliance (N,%)	31 (50)	34 (65)	31 (72)	96 (61)
Depth compliance (N,%)#	8 (14)	12 (26)	8 (27)	28 (21)
CCF compliance (N,%)	24 (39)	22 (42)	22 (51)	68 (43)
Overall compliance (N,%)#	0	2 (4)	3 (10)	5 (4)
CCF and CC rate compliance (N,%)	2 (3)	11 (21)	13 (30)	26 (17)
Depth and CCF compliance (N,%)#	0	4 (9)	4 (13)	8 (6)
Depth and Rate compliance (N,%)#	5 (8)	9 (20)	4 (13)	18 (13)
Survival to hospital discharge (N,%)	29 (47)	19 (37)	9 (21)	57 (36)
SHD with favorable neurologic outcome (N,%)*	19 (32)	15 (29)	6 (14)	40 (26)

line at the time of the ECPR event, and duration of CPR, guideline compliance for any CC metric was not significantly associated with SHD. However, age and duration of CPR were significantly associated with SHD, as 8-<18-year-olds had 64% lower odds of SHD than < 1-year olds (aOR = 0.36 {0.17, 0.76}; $P = 0.007$) and every minute increase in duration of CPR decreased odds of SHD by 2% (aOR = 0.98 {0.96,1.0}; $P = 0.02$). Because of the sample size, exact conditional logistic regressions were used to assess the relationship between compliance and SHD with FNO. Age group, indwelling arterial line, duration of CPR and within-group correlation in-hospital were adjusted in the models. The regression results demonstrated no statistical association between any compliance metric (CC depth, CC rate, CCF) and SHD with favorable neurologic outcome.

Discussion

In this multicenter retrospective cohort study, we are the first to assess the association between adherence to American Heart Association CPR chest compression quality metrics and survival to hospital discharge among pediatric patients undergoing extracorporeal cardiopulmonary resuscitation after in-hospital cardiac arrest. In this cohort there were no survival to hospital discharge benefits found among pediatric ECPR patients who received guideline-compliant CPR compared to patients who did not receive guideline-complaint CPR, however, there was only 14% of the entire cohort who met the predefined definition of compliance. After adjusting for age, presence of an indwelling arterial line at the time of the ECPR event, and duration of CPR, guideline compliance for any CC metric (rate, depth, fraction) was still not significantly associated with SHD or SHD with favorable neurologic outcome. Older patients and those with longer duration CPR had worse SHD outcomes irrespective of guideline-compliant CPR. The findings provide important insights into the role of CPR quality metrics, patient characteristics, and CPR duration in outcomes for this critically ill population.

Prior studies in adults, adolescents, older children and animal studies have demonstrated an association between CPR quality and survival outcomes, particularly as it pertains to CCF[15–17] and CC depth.[18–21] In 2014 Sutton et at. were the first to investigate the association of CPR quality with survival outcomes during pediatric resuscitations in a single center observational study.[19] In children > 1 year of age, the authors reported an association between performance of CPR compliant with the 2010 AHA chest compression depth recommendations ($\geq$ 51 mm) and higher rates of ROSC and 24-hour survival after IHCA.[19] All prior studies on CPR quality and outcomes, however, have evaluated chest compression quality metrics during *conventional* CPR only, and not during CPR events that are unresponsive to conventional CPR and require cannulation onto ECMO during the cardiac arrest event (ECPR).

The primary finding of this study is the lack of association between guideline-compliant CPR metrics (rate, depth, and fraction) and SHD or FNO. This is consistent across age groups and remained unchanged after adjusting for age, presence of an arterial line, and CPR duration. Notably, adherence to depth and fraction compliance was particularly low across all age groups, with overall compliance (rate, depth, and fraction combined) being exceptionally rare with 0% in the infant (<1year) age group. Despite theoretical advantages of high-quality CPR, this study did not demonstrate improved outcomes associated with chest compression guideline-compliance, emphasizing the need to consider other factors in the ECPR process. These findings corroborate the findings from the first publication from PediRES-Q which characterized the quality of pediatric in-hospital CC quality metrics during conventional CPR and found that CCs often do not meet AHA guideline CCF, CC rate and CC depth targets. Compliance was poor for both infants and children, with the most difficulty in achieving compliance with current guideline CC depth in younger children (CCF < 1 year, 1-<8years, 8-<18 years respectively: 53%, 81%, and 78%; CC rate: 32%, 50%, and 63%; CC depth 13%, 19%, and 44%; total compliance (meeting all three guideline targets): 8%, 2%, and 22%.[13]

Our study findings reinforce existing literature that older pediatric patients and prolonged resuscitation efforts are predictors of poorer outcomes.[11,22–26] Our results confirmed adolescents (8–18 years) exhibited a 64% lower likelihood of SHD compared to infants (<1 year), and that each minute increase in CPR duration was associated with a 2% decrease in the odds of SHD. While prior studies have highlighted the importance of CPR quality metrics in IHCA outcomes,[13,16] the findings here suggest that the context of ECPR may differ. Prior studies from the pediRES-Q collaborative have emphasized the importance of high-quality chest compressions in conventional CPR with higher chest compression depth and rate compliance positively associated with return of spontaneous circula-

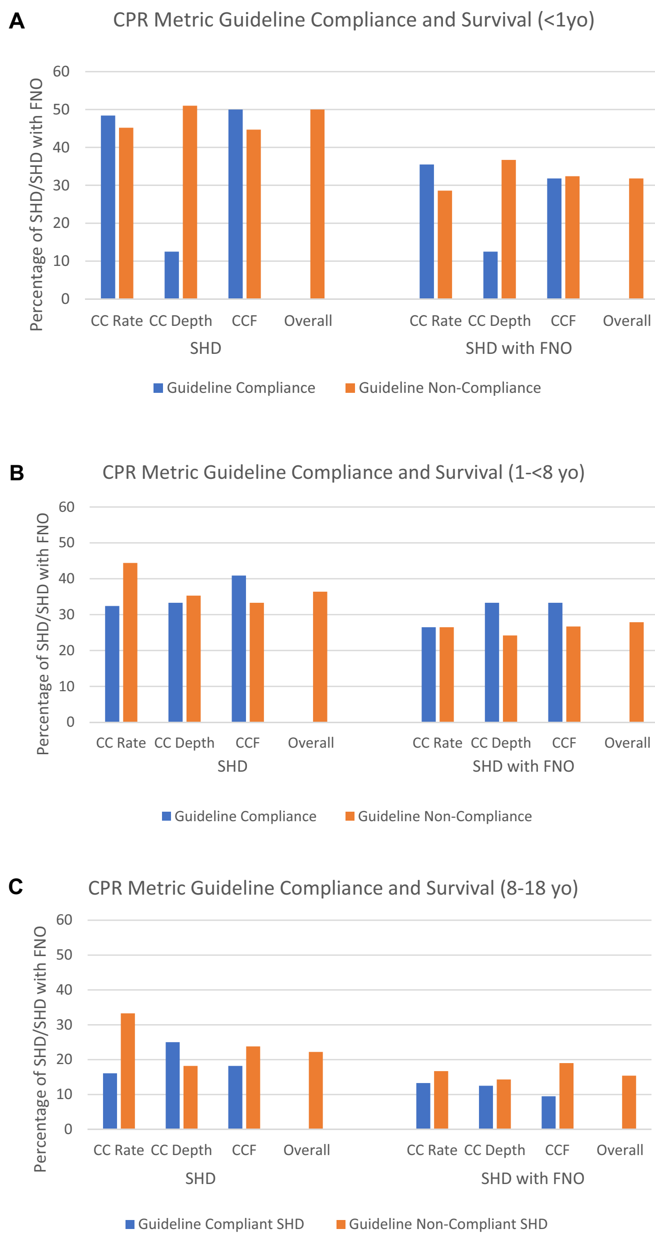

Fig. 2 – A). CPR Metric Guideline Compliance and Survival (<1yo). B). CPR Metric Guideline Compliance and Survival (1-<8 yo). C). CPR Metric Guideline Compliance and Survival (8–18 yo).

tion (ROSC) and survival in pediatric resuscitation events, emphasizing the need for real-time feedback and training to optimize CPR quality.[13] However, the complex interplay of ECPR—including the initiation of extracorporeal membrane oxygenation (ECMO)—may overshadow the isolated contributions of CPR quality metrics during the pre-ECMO period.

These findings underscore the complexity of ECPR in pediatric IHCA and suggest that a singular focus on CPR guideline compliance may be insufficient to improve outcomes. Efforts to optimize ECPR should consider patient age, timely initiation of ECMO, and strategies to minimize CPR duration. Investigating the role of other resuscitation factors, such as team dynamics, ECMO cannulation efficiency, and post-arrest care, may yield actionable insights. As an example, Lauridsen et al. recently demonstrated that during the last 5 min of recorded CPR prior to ECMO cannulation, each 5-sec increase in longest CC pause duration was associated with lower odds of survival to hospital discharge [adjusted OR 0.89, 95%CI: 0.79–0.99] and lower odds of survival with favorable neurological outcome [adjusted OR 0.77, 95%CI: 0.60–0.98], after controlling for age and CPR duration.[27] Further research is needed to explore whether specific subgroups (e.g. single ventricle cardiac patients) benefit more from adherence to AHA CPR guidelines and to assess the mechanistic pathways through which CPR quality impacts ECPR outcomes. Additionally, prospective studies incorporating advanced monitoring technologies and evaluating real-time interventions are warranted to refine resuscitation strategies.

Limitations

Several limitations should be noted. First, the retrospective design introduces the potential for unmeasured confounding. The cohort

Table 3 – Survival Outcomes by compliance by age group.

	Compliance Yes	*Compliance No*	*P value*[€]
<1 year (N = 62)			
Rate compliance			
N	31	31	–-
SHD (N,%)	15(48.4)	14(45.2)	>0.99
SHD with favorable neurologic outcome (N,%)*	11(35.5)	8(28.6)	0.59
Depth compliance[#]			
N	8	51	–
SHD (N,%)	1(12.5)	26(51.0)	0.06
SHD with favorable neurologic outcome (N,%)*	1(12.5)	18(36.7)	0.25
CCF compliance			
N	24	38	–
SHD (N,%)	12(50.0)	17(44.7)	0.8
SHD with favorable neurologic outcome (N,%)*	7(31.8)	12(32.4)	>0.99
Overall compliance			
N	35	24	–
SHD (N,%)	0(0.0)	12(50.0)	–
SHD with favorable neurologic outcome (N,%)*	0(0.0)	7(31.8)	–
1-<8 years (N = 52)			
Rate compliance			
N	34	18	–
SHD (N,%)	11(32.4)	8(44.4)	0.55
SHD with favorable neurologic outcome (N,%)*	9(26.5)	6(35.3)	0.53
Depth compliance[#]			
N	12	34	–
SHD (N,%)	4(33.3)	12(35.3)	>0.99
SHD with favorable neurologic outcome (N,%)*	4(33.3)	8(24.2)	0.7
CCF compliance			
N	22	30	–
SHD (N,%)	9(40.9)	10(33.3)	0.77
SHD with favorable neurologic outcome (N,%)*	7(33.3)	8(26.7)	0.76
Overall compliance[#]			
N	2	44	–
SHD (N,%)	0(0.0)	16(36.4)	0.54
SHD with favorable neurologic outcome (N,%)*	0(0.0)	12(27.9)	>0.99
8–18 years (N = 43)			
Rate compliance			
N	31	12	–
SHD (N,%)	5(16.1)	4(33.3)	0.24
SHD with favorable neurologic outcome (N,%)*	4(13.3)	2(16.7)	>0.99
Depth compliance[#]			
N	8	22	–
SHD (N,%)	2(25.0)	4(18.2)	0.65
SHD with favorable neurologic outcome (N,%)*	1(12.5)	3(14.3)	>0.99
CCF compliance			
N	22	21	–
SHD (N,%)	4(18.2)	5(23.8)	0.72
SHD with favorable neurologic outcome (N,%)*	2(9.5)	4(19.0)	0.66
Overall compliance [#]			
N	3	27	–
SHD (N,%)	0(0.0)	6(22.2)	>0.99
SHD with favorable neurologic outcome (N,%)*	0(0.0)	4(15.4)	>0.99

[#] 22 events with single sensor, Dual AA or incorrect sensor position documented were excluded for depth related analysis. (3 in < 1 year, 6 in 1-<8 years, 13 in 8–18 years).

* 5 arrests with missing favorable neurologic outcome information. (3 in < 1 year, 1 in 1-<8; years, 1 in 8–18 years).

[€] p value for fisher's exact test.

from the pediRES-Q collaborative may not be representative of all hospitals, as participating sites are typically dedicated to improving CPR quality and may have specialized expertise. Additionally, the exclusion of patients with an open chest due to inability to place dual sensor defibrillator pads, or incomplete data, likely skews the sample toward older children and excludes critical data points. Depth compliance was particularly challenging to achieve and measure accurately, potentially due to limitations of accelerometer technology or variations in patient anatomy. Another key limitation is the small number of patients achieving overall compliance with AHA metrics. With only five such cases, and none in the infant age group, the study's ability to assess the full impact of

Table 4 – Multivariable Logistic Regression Model for Assessing the Relationship between Chest Compression Rate, Depth, and Fraction Compliance and SHD.

	SHD (N, %)	*Adjusted Odds Ratio*	*95% CI*	*P value*
Model 1[#]				
Age Group				
< 8 years	48 (42.1)	1.00	–	–
8–18 years	9 (20.9)	0.36	(0.17, 0.76)	0.007
AHA Depth Compliant CPR (Relative depth)				
Yes	7 (25.0)	0.52	(0.22, 1.22)	0.13
No	42 (39.3)	1.00	–	–
Arterial line presence				
Yes	28 (42.4)	1.33	(0.56, 3.17)	0.51
No	29 (31.9)	1.00	–	–
Duration of CPR	–	0.98	(0.96, 1.00)	0.02
Model 2				
Age Group				
< 8 years	48 (42.1)	1.00	–	–
8–18 years	9 (20.9)	0.37	(0.18, 0.75)	0.006
AHA Rate Compliant CPR				
Yes	31 (32.3)	0.75	(0.32, 1.19)	0.52
No	26 (42.6)	1.00	–	–
Arterial line presence				
Yes	28 (42.4)	1.36	(0.55, 3.35)	0.51
No	29 (31.9)	1.00	–	–
Duration of CPR	–	0.98	(0.97, 1.00)	0.01
Model 3				
Age Group				
< 8 years	48 (42.1)	1.00	–	–
8–18 years	9 (20.9)	0.36	(0.18, 0.71)	0.003
AHA CCF Compliant CPR				
Yes	25 (36.8)	1.16	(0.65, 2.09)	0.61
No	32 (36.0)	1.00	–	–
Arterial line presence				
Yes	28 (42.4)	1.35	(0.56, 3.23)	0.50
No	29 (31.9)	1.00	–	–
Duration of CPR	–	0.98	(0.97, 1.00)	0.01

Multivariable logistic regressions with random site effect were used to assess the relationship between compliance and survival to hospital discharge adjusting for age group, art line, and CPR duration. [#] 22 events with single sensor, Dual AA or incorrect sensor position documented were excluded for depth related analysis. (3 in < 1 year, 6 in 1-<8 years, 13 in 8–18 years).

Because of the sample size, exact conditional logistic regressions were used to assess the relationship between compliance and survival to hospital discharge with favorable neurological outcome. Age group, art line, duration of CPR and within-group correlation in hospital were adjusted in the models. The regression results demonstrated no statistical association between any compliance (depth, rate, CCF) and SHD with favorable neurologic outcome. The number of patients with overall compliance is only 5 and none achieved SHD, logistic regression model cannot be conducted.

*5 arrests with missing favorable neurologic outcome information. (3 in < 1 year, 1 in 1-<8 years, 1 in 8–18 years).

[#] 22 events with single sensor, dual anterior-apical or incorrect sensor position documented were excluded from depth related analysis. (3 in < 1 year, 6 in 1-<8 years, 13 in 8–18 years).

guideline-compliant CPR is constrained. We did not investigate how other guideline-compliant factors such as frequency of epinephrine dosing or time to defibrillation, among others, may play a role in CPR quality and outcomes. Moreover, potential differences in outcomes among patients with single-ventricle physiology, known to be a high-risk group for cardiac arrest, were not evaluated. Future studies should aim to address these gaps and incorporate detailed analyses of underlying conditions. Finally, the definitions of AHA guideline compliant CPR targets, while based upon the best available science[28,29] and consistent with previous publications,[18,19,21], are somewhat arbitrary and based upon expert consensus. We cannot be certain that the current AHA quality targets are the optimal cutoffs for survival. Additionally, 37% of the events noted that physiologic monitoring of some type (arterial line, CVP, EtCO[2,] NIRS) was used to guide CPR, thus it is possible that physiologic targets were used as guidelines rather than CC quality metrics. Prior pediatric studies have shown diastolic blood pressure,[30] EtCO2,[31] and NIRS[32] to be associated with survival outcomes. It is also possible that guideline CC targets of depth for example do not necessarily correlate with the depth required to achieve an adequate DBP (>25 mmHg in infants and > 30 mmHg in children). Future optimal cutoffs for CCF, CC rate, and CC depth targets represent a significant gap in the pediatric resuscitation science knowledge base that requires further study. However, for the first time, this multicenter pediatric IHCA pediRES-Q quality improvement collaborative describes the landscape of CPR quality for children undergoing ECPR and provides new benchmark information on the translation and implementation of pediatric guidelines for IHCA not responsive to conventional CPR and requiring ECPR.

Conclusion

This study highlights the complex interplay of factors influencing outcomes in pediatric ECPR. Our findings suggest there is no association with chest compression quality metric compliance and SHD or SHD with FNO in pediatric ECPR, however, these findings must be tempered by the overall low compliance with AHA guidelines. Consistent with prior studies both patient age and CPR duration were significant predictors for survival outcomes. These findings emphasize the need for tailored, multifaceted approaches to better understand factors associated with survival after pediatric ECPR of all ages while also helping to drive improvements in ECPR care models.

CRediT authorship contribution statement

Tia T. Raymond: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Priscilla Yu:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Ivie Esangbedo:** Writing – review & editing. **Todd Sweberg:** Writing – review & editing. **Javier J. Lasa:** Methodology, Writing – review & editing, Supervision. **Xuemei Zhang:** Formal analysis, Project administration, Writing – review & editing. **Heather Griffis:** Formal analysis, Project administration, Writing – review & editing. **Vinay Nadkarni:** Writing – review & editing, Project administration, Supervision.

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Declaration of competing interest

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REFERENCES

1. Holmberg MJ, Ross CE, Fitzmaurice GM, et al. Annual incidence of adult and pediatric in-hospital cardiac arrest in the United States. Circ Cardiovasc Qual Outcomes 2019;12:e005580.
2. Bhanji F, Topjian AA, Nadkarni VM, et al. for the American heart association's get with the guidelines-resuscitation investigators. survival rates following Pediatric in-hospital cardiac arrests during nights and weekends. JAMA Pediatr 2017;171:39–45.
3. Maconochie IK, Aickin R, Hazinski MF, et al. Pediatric life support: 2020 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. Circulation 2020;142:S140–84.
4. Maconochie IK, de Caen AR, Aickin R, et al. Part 6: Pediatric basic life support and pediatric advanced life support: 2015 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations. Resuscitation 2015;95:e147–68.
5. Tonna JE, Selzman CH, Girotra S, et al. for the American heart association's get with the guidelines-resuscitation investigators. resuscitation using ECPR during in-hospital cardiac arrest (RESCUE-IHCA) mortality prediction score and external validation. JACC Cardiovasc Interv 2022;15:237–47.
6. Topjian AA, Raymond TT, Atkins D, et al. Part 4: Pediatric basic and advanced life support: 2020 american heart association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2020;142:S469–523.
7. Conrad SA, Broman LM, Taccone FS, et al. The extracorporeal life support organization maastricht treaty for nomenclature in extracorporeal life support. a position paper of the extracorporeal life support organization. Am J Respir Crit Care Med 2018;198:447–51.
8. Bembea MM, Ng DK, Rizkalla N, et al. for the American heart association's get with the guidelines - resuscitation investigators. outcomes after extracorporeal cardiopulmonary resuscitation of pediatric in-hospital cardiac arrest: a report from the get with the guidelines-resuscitation and the extracorporeal life support organization registries. Crit Care Med 2019;47:e278–85.
9. Delmo Walter EM, Alexi-Meskishvili V, Huebler M, et al. Rescue extracorporeal membrane oxygenation in children with refractory cardiac arrest. Interact Cardiovasc Thorac Surg 2011;12:929–34.
10. Fagnoul D, Combes A, De Backer D. Extracorporeal cardiopulmonary resuscitation. Curr Opin Crit Care 2014;20:259–65.
11. Sivarajan VB, Best D, Brizard CP, Shekerdemian LS, d'Udekem Y, Butt W. Duration of resuscitation prior to rescue extracorporeal membrane oxygenation impacts outcome in children with heart disease. Intensive Care Med 2011;37:853–60.
12. Kane DA, Thiagarajan RR, Wypij D, et al. Rapid-response extracorporeal membrane oxygenation to support cardiopulmonary resuscitation in children with cardiac disease. Circulation 2010;122: S241–8.
13. Niles DE, Duval-Arnould J, Skellett S, et al. Characterization of pediatric in-hospital cardiopulmonary resuscitation quality metrics across an international resuscitation collaborative. Pediatr Crit Care Med 2018;19:421–32.
14. Raymond TT, Cunnyngham CB, Thompson MT, Thomas JA, Dalton HJ, Nadkarni VMfor the American Heart Association National Registry of CPR Investigators. Outcomes among neonates, infants, and children after extracorporeal cardiopulmonary resuscitation for refractory inhospital pediatric cardiac arrest: a report from the National Registry of Cardiopulmonary Resuscitation. Pediatr Crit Care Med 2010;11:362–71.
15. Cheskes S, Schmicker RH, Christenson J, et al. Perishock pause: an independent predictor of survival from out-of-hospital shockable cardiac arrest. Circulation 2011;124:58–66.
16. Christenson J, Andrusiek D, Everson-Stewart S, et al. Chest compression fraction determines survival in patients with out-of-hospital ventricular fibrillation. Circulation 2009;120:1241–2127.
17. Vaillancourt C, Everson-Stewart S, Christenson J, et al. Resuscitation Outcomes Consortium Investigators. The impact of increased chest compression fraction on return of spontaneous circulation for out-of-hospital cardiac arrest patients not in ventricular fibrillation. Resuscitation 2011;82:1501–2157.
18. Stiell IG, Brown SP, Nichol G, et al. What is the optimal chest compression depth during out-of-hospital cardiac arrest resuscitation of adult patients?. Circulation 2014;130:1962–70.
19. Sutton RM, French B, Niles DE, et al. 2010 American Heart Association recommended compression depths during pediatric in-

hospital resuscitations are associated with survival. Resuscitation 2014;85:1179–84.
20. Vadeboncoeur T, Stolz U, Panchal A, et al. Chest compression depth and survival in out-of-hospital cardiac arrest. Resuscitation 2014;85:182–218.
21. Stiell IG, Brown SP, Christenson J, et al. What is the role of chest compression depth during out-of-hospital cardiac arrest resuscitation?. Crit Care Med 2012;40:1192–2118.
22. O'Halloran A, Morgan RW, Kennedy K, et al. Characteristics of Pediatric In-Hospital Cardiac Arrests and Resuscitation Duration. JAMA Netw Open 2024;7:e2424670.
23. Berg RA, Nadkarni VM, Clark AE, et al. Incidence and outcomes of cardiopulmonary resuscitation in PICUs. Crit Care Med 2016;44:798–808.
24. Matos RI, Watson RS, Nadkarni VM, et al. Duration of cardiopulmonary resuscitation and illness category impact survival and neurologic outcomes for in-hospital pediatric cardiac arrests. Circulation 2013;127:442–51.
25. Meaney PA, Nadkarni VM, Cook EF, et al. Higher survival rates among younger patients after pediatric intensive care unit cardiac arrests. Pediatrics 2006;118:2424–33.
26. Al-Eyadhy A, Almazyad M, Hasan G, et al. Outcomes of cardiopulmonary resuscitation in the pediatric intensive care of a tertiary center. J Pediatr Intensive Care 2023;12:303–11.
27. Lauridsen KG, Lasa JJ, Raymond TT, et al. Association of chest compression pause duration prior to E-CPR cannulation with cardiac arrest survival outcomes. Resuscitation 2022;177:85–92.
28. Atkins DL, Berger S, Duff JP, et al. Part 11: Pediatric basic life support and cardiopulmonary resuscitation quality: 2015 American Heart Association Guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2015;132:S519S525.
29. Meaney PA, Bobrow BJ, Mancini ME, et al. CPR Quality Summit Investigators, the American Heart Association Emergency Cardiovascular Care Committee, and the Council on Cardiopulmonary, Critical Care, Perioperative and Resuscitation: Cardiopulmonary resuscitation quality: [corrected] Improving cardiac resuscitation outcomes both inside and outside the hospital: A consensus statement from the American Heart Association. Circulation 2013;128:417435.
30. Berg RA, Sutton RM, Reeder RW, et al. Association between diastolic blood pressure during pediatric in-hospital cardiopulmonary resuscitation and survival. Circulation 2018 Apr 24;137(17):1784–95.
31. Morgan RW, Reeder RW, Bender D, et al. Associations between end-tidal carbon dioxide during pediatric cardiopulmonary resuscitation, cardiopulmonary resuscitation quality, and survival. Circulation 2024 Jan 30;149(5):367–78.
32. Raymond TT, Esangbedo ID, Rajapreyar P, et al. Cerebral oximetry during pediatric in-hospital cardiac arrest: a multicenter study of survival and neurologic outcome. Crit Care Med. 2024 May 1;52 (5):775–85.