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Clinical paper

Cardiopulmonary resuscitation employing only abdominal compressions in infants after cardiac surgery: A secondary sub-analysis of the ICU-RESUS study

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Abstract

Importance: Patients with underlying cardiac disease form a considerable proportion of pediatric patients who experience in-hospital cardiac arrest. In pediatric patients after cardiac surgery, CPR with abdominal compressions alone (AC-CPR) may provide an alternative to standard chest compression CPR (S-CPR) with additional procedural and physiologic advantages.

Objective: Quantitatively describe hemodynamics during cardiopulmonary resuscitation (CPR) and outcomes of infants who received only abdominal compressions (AC-CPR).

Design: This is a sub-group analysis of the prospective, observational cohort from the ICU-RESUS trial NCT028374497.

Setting & Patients: A single site quaternary care pediatric cardiothoracic intensive care unit enrolled in the ICU-RESUS trial. Patients less than 1 year of age with congenital heart disease who required compressions during cardiac arrest.

Interventions: Use of AC-CPR during cardiac arrest resuscitation.

Measurements and Main Results: Invasive arterial line waveforms during CPR were analyzed for 11 patients (10 surgical cardiac and 1 medical cardiac). Median weight was 3.3 kg [IQR 3.0, 4.0]; and median duration of CPR was 5.0 [3.0, 20.0] minutes. Systolic (median 57 [IQR 48, 65] mmHg) and diastolic (median 32 [IQR 24, 43] mmHg) blood pressures were achieved with a median rate of 114 [IQR 100, 124] compressions per minute. Return of spontaneous circulation was obtained in 9 of 11 (82%) patients; 2 patients (18%) were cannulated for extracorporeal cardiopulmonary resuscitation (ECPR) and 6 (55%) survived to hospital discharge with favorable neurologic outcome.

Conclusions: AC-CPR may offer an alternative method to maintain perfusion for infants who experience cardiac arrest. This may have particular benefit in pediatric patients after cardiac surgery for whom external chest compressions may be harmful due to anatomic and physiologic considerations.

Keywords: Compressions, Abdominal compressions, Cardiopulmonary resuscitation, Pediatric cardiac intensive care

Introduction

Chest compressions, or external cardiac massage, was first reported in the mid-19th century, but it was not until the 1960′s that these were accepted as a cornerstone of cardiopulmonary resuscitation (CPR).[1] Over the past several decades, great attention has been focused on optimizing standard chest compressions (S-CPR) by focusing on rate, depth, recoil, and compression fraction.[2–6] Despite an increased frequency of pediatric in-hospital cardiac arrest, focus on

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optimal resuscitation methods has contributed to a decline in mortality.[7] Among pediatric patients, those with congenital or acquired heart disease are at significantly increased risk of experiencing cardiac arrest. [8,9] It is well recognized that these patients pose unique challenges during CPR due to variations in anatomy and physiology, sometimes requiring modified approaches to S-CPR.[10–12] Both the Society of Thoracic Surgeons and the European Association for Cardio-Thoracic Surgery have proposed that the post-operative cardiac patient who experiences cardiopulmonary arrest differs sufficiently from standard patients as to warrant a modified approach to resuscitation. Although there is a paucity of clinical data to support this approach, both groups acknowledge that CPR employing only abdominal compressions (AC-CPR) may provide theoretical benefits during resuscitation in the setting of the cardiac intensive care unit.[13,14]

Based on reported experimental data and local anecdotal experience, AC-CPR was utilized in clinical care for select patients who experienced cardiac arrest in the cardiothoracic-intensive care unit. The objective of this single-center, prospective, observational cohort study was to quantitatively describe hemodynamics and outcomes of these patients by leveraging data collected as part of the ICU-RESUScitation trial–a multicenter interventional trial of physiologic-focused point-of-care CPR training and debriefing completed in the Collaborative Pediatric Critical Care Research Network (CPCCRN).

Materials and methods

Setting and design

The ICU-RESUS study (trial number NCT028374497) is a National Heart, Lung, and Blood Institute (NHLBI)-funded prospective, multicenter trial conducted across the Collaborative Pediatric Critical Care Research Network (CPCCRN), a *Eunice Kennedy Shriver* National Institute of Child Health and Human Development (NICHD)-funded research collaborative.[15] The institutional review boards of each clinical site and of the CPCCRN Data Coordinating Center (DCC) at the University of Utah approved this study protocol with waiver of informed consent. The University of Utah Institutional Review Board (IRB) served as the central IRB and approved the ICU-RESUS study protocol with waiver of informed consent (protocol IRB_00093320) on July 18, 2016. Procedures were followed in accordance with the ethical standards of the central IRB and with the Helsinki Declaration of 1975.

Patients were included in ICU-RESUS if they were 1) neonates at 37 weeks gestational age or older up to, and including, 18 years of age; and 2) received CPR in the ICU setting.

We specifically report the findings of a small cohort of 11 ICU-RESUS patients, cared for at a single institution, who received AC-CPR. Data collected on each subject included Utstein-style standardized cardiac arrest and CPR data, including but not limited to demographics, preexisting conditions, illness categories, interventions in place at time of arrest, first documented rhythm, immediate cause of arrest, duration of CPR, and resuscitation interventions.[16] Patient outcome data collected included immediate outcome of the CPR event (ROSC for greater than or equal to 20 min, transition to ECMO, death), survival to hospital discharge, survival to hospital discharge with favorable neurologic outcome, changes in functional status of survivors (using Functional Status Scale (FSS) scores), and the presence of new morbidity in survivors.[17] Survival to hospital discharge with a favorable neurologic outcome was defined as Pediatric Cerebral Performance Category (PCPC) 1–3 or no worse than pre-arrest PCPC, as per recommended guidelines.[16,18,19] The illness categories included in this analysis were determined as either surgical cardiac or medical cardiac using definitions from the AHA "Get with the Guidelines-Resuscitation" registry.[20] Surgical cardiac illness category specifically includes only patients who are postoperative following cardiac surgery at the time of the event. Medical cardiac illness category includes patients with a primary medical illness that is cardiovascular at the time of the event, but the event does not occur in the postoperative period.[21]

Measurements

Physiologic waveform data for up to 20 min from the initiation of compressions were analyzed as previously reported.[22,23] Analyzed data included invasively measured systolic arterial blood pressure (mmHg) and diastolic arterial blood pressure (mmHg). Additionally, data on compression quality, including rate and chest compression fraction, were derived from the available waveform data. Data extraction methodology has previously been published for systolic, diastolic, and mean blood pressure,[22] chest compression rate and fraction,[4] ventilation rate, and end-tidal CO2 analysis.[24] For patients with both invasive arterial blood pressure and central venous or right atrial monitoring available, coronary perfusion pressure was calculated as the difference between diastolic blood pressure and minimum diastolic central venous pressure (as a surrogate for right atrial pressure) or directly measured right atrial pressure. The diastolic right atrial pressure was the minimum central venous pressure value for each chest compression. Diastolic blood pressure was calculated as previously described.[15,23,25]

Description of technique

AC-CPR is a novel intervention in the setting of a pediatric cardiothoracic intensive care unit. Abdominal compressions were initiated at the discretion of the attending physician serving as code team leader and the cardiothoracic surgeon present during the arrest. Compressors identified a midline point between the xiphisternum and the umbilicus where compressions were initiated. Interposed chest compressions were not performed. Compressors maintain visualization of the arterial waveform during compressions to ensure adequate hemodynamics. Compressions were initiated by an attending physician and, when a change of compressors became necessary, the initiating compressor closely directed their replacement to ensure similar hand placement and adequate hemodynamics with the transition to a new compressor.

The clinical practice at this institution has been to utilize AC-CPR only in those patients with invasive hemodynamic monitoring providing immediate, real-time feedback on the quality of compressions. The resuscitation team could utilize any method of compressions that resulted in acceptable hemodynamics as defined by the resuscitation team and may have switched techniques throughout the resuscitation. As part of study data collection during post-event debriefing, the CPR technique(s) utilized was noted as well as the specific time course if method of compressions was switched by the resuscitation team.

Clinical experience with abdominal compressions at study site

Our initial experience, prior to this cohort, involved a patient with concerns for sternal stability after median sternotomy, who experienced cardiac arrest following a complex cardiac repair. Under the guidance of the pediatric cardiothoracic surgeon and critical care attending who were present at the start of that arrest, abdominal compressions were initiated and guided by invasive arterial and central venous monitoring. Beginning in 2015, we started employing AC-CPR on a limited basis as our unit gained experience and skill in its use. When our group initially deployed this intervention, it was limited to pre-identified patients who were considered high-risk for arrest and for whom external chest compressions were felt to be potentially dangerous. Over time our practice expanded, such that any patient could be a candidate for abdominal compressions provided they had invasive arterial blood pressure monitoring. The decision to transition to AC-CPR remained exclusively at the discretion of the attending physician or surgeon present at the code and was driven by assessment of hemodynamics during resuscitation. If adequate hemodynamics could not be achieved or sustained with AC-CPR, the team would transition to S-CPR. There was no formal protocol for provision of AC-CPR at our institution. Due to the limited use of this approach and absence of formal training, all staff are directed to begin with S-CPR during any code event.

Statistical analysis

Patient and event characteristics were summarized using frequencies and percentages or medians and interquartile ranges. Event level averages were used for outcome analysis. Adequate compression rate (>100 and ≤ 120 per minute) and chest compression fraction (>0.8) was defined by the study protocol in accordance with ACC-AHA PALS guidelines.[12]

Results

Twelve patients were identified who underwent AC-CPR at our institution during the study period. One patient was excluded due to unclear transition from S-CPR to AC-CPR. All patients in this series were younger than 6 months of age and had undergone an intervention for congenital heart disease (Table 1). Ten patients underwent surgical procedures with a median STAT category of 4 (range 3–5) (Table 1); one patient had an interventional cardiology procedure. Two patients had open chests at the time of arrest, including one supported by ECMO with central cannulation; another two patients had their chests opened during resuscitative efforts. Nearly all the patients were receiving vasoactive infusions (n = 9) and mechanical ventilation (n = 10) at the time of arrest. Immediately prior to arrest, eight patients experienced hypotension, two arrhythmias, and one respiratory failure.

CPR was performed for a median duration of 5 min [IQR 3,20]. (Table 2). The median compression rate during AC-CPR was 114 [IQR 100, 124]. During AC-CPR, median systolic blood pressure was 57 mmHg [IQR 48, 65] and median diastolic blood pressure was 32 mmHg [IQR 23, 43]. (Fig. 1) Continuous central venous pressure (CVP) or right atrial pressure (RAP) monitoring was available for 11 patients. The median CVP/RAP during AC-CPR was 12.2 mmHg [IQR 8.6, 26.9]. This allowed for calculation of estimated coronary perfusion pressure (CoPP) in those patients (difference between diastolic blood pressure and mean diastolic CVP). Median CoPP value during AC-CPR was 12.6 mmHg [IQR 3.3, 20.4]. ETCO2 waveforms were available for analysis in nine of the patients. The median ETCO2 values during resuscitation were 13.3 mmHg [IQR 11.5, 25.6]. (Table 3).

Table 1 – Demographics and pre-event characteristics.

	Overall (N = 11)
Demographics	
Age	
<1 month	8 (72.7%)
1 month-<1 year	3 (27.3%)
Weight (kg)	3.3 [3.0, 4.0]
Male	4 (36.4%)
Race	
White	7 (63.6%)
Black or African American	2 (18.2%)
Other	2 (18.2%)
Conditions present at the start of resuscitation	
Respiratory insufficiency	9 (81.8%)
Hypotension	9 (81.8%)
Congestive heart failure	1 (9.1%)
Renal insufficiency	1 (9.1%)
Pulmonary hypertension	1 (9.1%)
ECMO	1 (9.1%)
Congenital heart disease	11 (100.0%)
Transposition of the great vessels	4 (36.4%)
Hypoplastic left heart syndrome	2 (18.2%)
Aortic stenosis, Mitral Stenosis	1 (9.1%)
Aortic Arch Hypoplasia and VSD	1 (9.1%)
DORV with Pulmonic Stenosis	1 (9.1%)
Truncus Arteriosus	1 (9.1%)
Tetralogy of Fallot	1 (9.1%)
Pre-event characteristics	
Illness category	
Medical cardiac	1 (9.1%)
Surgical cardiac	10 (90.9%)
STAT[4] Category	4 (3–5)
PRISM[1]	7.0 [2.0, 10.0]
Vasoactive inotropic score[2]	2.5 [1.5, 9.5]
Baseline PCPC score[3]	
1 – Normal	10 (90.9%)
4 – Severe disability	1 (9.1%)
Baseline FSS[3]	6.0 [6.0, 6.0]

PRISM = Pediatric RISk of Mortality; PCPC = Pediatric Cerebral Performance Category; FSS = Functional Status Scale.

[1] PRISM was evaluated 2–6 h prior to the event.

[2] Vasoactive-inotropic score was evaluated 2 h prior to the event.

[3] Baseline PCPC and FSS represent subject status prior to the event leading to hospitalization.

[4] Society of Thoracic Surgeons – European Association of Cardiothoracic Surgery Category.

Table 4 shows outcomes of these 11 patients and outcomes of the cardiac surgical patients in the ICU-RESUS parent study (the latter previously published). Eight patients (73%) achieved sustained ROSC > 20 min after their event and two patients required extracorporeal membrane oxygenation (E-CPR) to attain return of circulation (ROC; Table 4). Six patients (55%) survived to hospital discharge, all with a favorable neurologic outcome. Median FSS prior to arrest was 6 [IQR 6, 6]; median FSS at time of discharge among survivors was 7 [IQR 6, 8] (Table 4). Because of the small number of patients in our clinical series of AC-CPR, we were not able to rigorously compare this group statistically with the ICU-RESUS cardiac surgical group while controlling for potential confounders. A review of the patients' charts showed that, among the 10 patients who survived > 24 h after arrest, two developed abdominal complications: one with necrotizing

Table 2 – Event characteristics.

	Overall (N = 11)
Interventions in place prior to event	
Central venous access[1]	10 (90.9%)
Left Lower Extremity PICC	1
Right Atrial Lines	6
Right Internal Jugular CVL	1
Right Lower Extremity PICC	1
Right Upper Extremity PICC	1
Umbilical Venous Catheter	2
Arterial Access[2]	11 (100%)
Radial Artery	7
Femoral Artery	2
Umbilical Artery	3
Vasoactive infusion	9 (81.8%)
Invasive mechanical ventilation	10 (90.9%)
Non-invasive ventilation	1 (9.1%)
End-tidal CO_2 monitoring	10 (90.9%)
Immediate cause(s) of event	
Arrhythmia	2 (18.2%)
Hypotension	8 (72.7%)
Respiratory decompensation	1 (9.1%)
Duration of CPR (minutes)	5.0 [3.0, 20.0]
Duration of CPR (minutes)	
<6	6 (54.5%)
6–15	2 (18.2%)
16–35	2 (18.2%)
>35	1 (9.1%)
CPR time[3]	
Weekday	9 (81.8%)
Weeknight	1 (9.1%)
Weekend	1 (9.1%)
Days since last cardiac surgery	0.0 [0.0, 0.0]
Sternum open at start of CPR event	2 (18.2%)
Minutes to sternum opening	22.0 [2.0, 42.0]
First documented rhythm	
Pulseless electrical activity / asystole	4 (36.4%)
Ventricular fibrillation / tachycardia	1 (9.1%)
Bradycardia with poor perfusion	6 (54.5%)
Pharmacologic interventions during event	
Epinephrine	11 (100.0%)
Minutes to first dose	1.0 [0.0, 3.0]
Number of doses	1.0 [1.0, 2.0]
Average interval between doses[4]	16.0 [6.0, 19.0]
Atropine	0 (0%)
Calcium	7 (63.6%)
Sodium bicarbonate	4 (36.4%)
Vasopressin	0 (0%)
Amiodarone	0 (0%)
Lidocaine	0 (0%)
Fluid bolus	1 (9.1%)

CPR = cardiopulmonary resuscitation.

[1] Two patients had multiple points of central access: One with RUE PICC and RIJ CVL; another with RA lines and a UVC.

[2] One patient had both umbilical and radial arterial lines in place during resuscitation.

[3] Weekday is between 7 AM and 11 PM Monday – Friday; weeknight is after 11 PM Monday – Thursday; Weekend is from 11 PM on Friday through 7 AM on the following Monday.

[4] Average interval between epinephrine doses is only calculated on subjects with at least 2 doses of epinephrine.

enterocolitis (NEC) diagnosed on radiograph and ultrasound within 24 h, and the second also with NEC, which developed 35 days after arrest. Both cases of NEC were treated without the need for surgery. There were no other abdominal complications identified during review of the clinical records.

Discussion

To our knowledge, this is the first clinical case series reporting the use of abdominal compressions alone for CPR. Previous clinical data, including ICU-RESUS data, have established that maintaining arterial diastolic pressure >25 mmHg in infants with external chest compressions is associated with superior rates of survival to hospital discharge.[21,22] The mean arterial diastolic pressures attained with AC-CPR was 32 [23, 43] mmHg, well above the >25 mmHg threshold.[4,22,26–28] The achievement of excellent hemodynamics during CPR with this technique was associated with sustained ROSC in 73% of these children and with survival to hospital discharge with favorable neurologic outcome in 55%.

Interest in incorporating abdominal compressions into CPR dates to the early 1980′s with the work of Ralston et al., who reported on interposed abdominal compressions during CPR.[29] Since that time, there have been several reports, both experimental and clinical, of successful resuscitation using this modality.[30,31] The focus of most studies has been on interposed abdominal compressions during CPR with far less published on the use of abdominal compressions alone. Geddes, et al., demonstrated that AC-CPR could provide excellent DBP during CPR in a swine model of ventricular fibrillation (VF).[27,28] Additionally, in post-mortem analysis, they saw no evidence of damage to the visceral organs.[28]

Several groups have come to recognize that traditional resuscitative measures may not be a one-size-fits-all approach among pediatric patients with congenital heart disease or after cardiac surgery. The Society of Thoracic Surgeons (STS) and the European Association for Cardio-Thoracic Surgery (EACTS) have advocated for modified resuscitation algorithms for adult and pediatric patients after cardiac surgery.[13,14] Both groups recommend utilizing available invasive hemodynamic monitoring during CPR and acknowledge the theoretical benefits of AC-CPR, while admitting that additional research is necessary before any recommendations can be made. This pilot report begins to highlight AC-CPR as a promising technique for these high-risk patients.

There are several conjectured benefits to AC-CPR, particularly in this patient population. AC-CPR allows for improved chest compression fraction (CCF) as there is less need to pause for procedures such as cannulation during ECPR or sternal opening. S-CPR relies on compressing the chest, necessarily increasing intrathoracic pressure. This limits venous return and cardiac pre-load during the active compression phase, with the only stimulus to venous return being recoil of the chest wall, which we conjecture may be compromised after recent sternotomy. AC-CPR is especially attractive for post-operative cardiac surgical patients as it allows protection of fresh post-operative suture lines as well as prevention of distortion of implants such as modified Blalock-Taussig-Thomas shunts or stents within the right ventricular outflow tract or patent ductus arteriosus. Several studies have shown that providing pressure on the abdomen during resuscitation may increase coronary perfusion pressure in porcine models.[32–34] The mechanisms may be complex, but an important component is presumably that compression of the abdominal contents can mobilize the large venous reservoirs of the splanchnic circulation to augment cardiac preload. While this would be

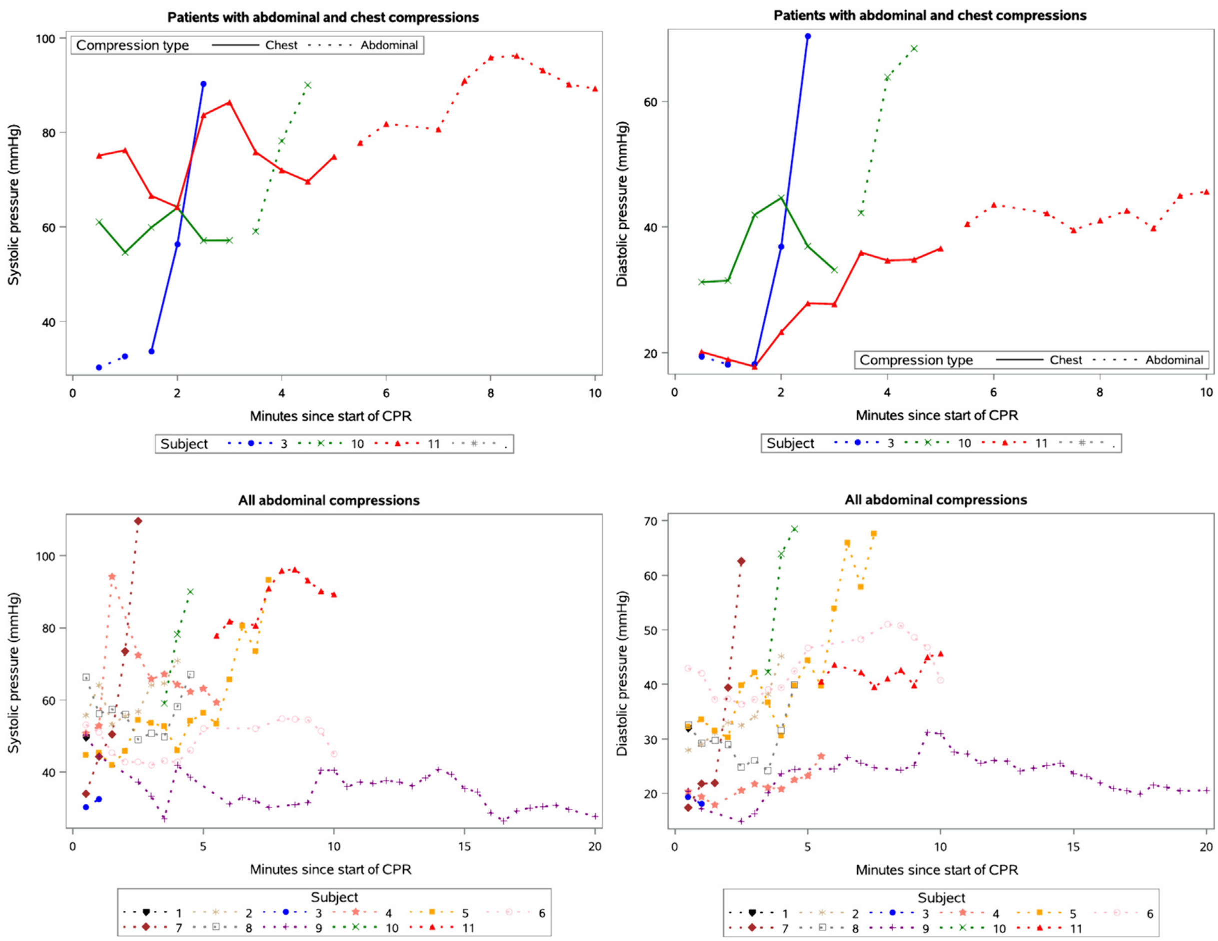

Fig. 1 – Systolic and diastolic blood pressures during CPR.

beneficial for any patient, certain congenital heart disease patients, particularly those with cavo-pulmonary connections such as the Glenn and Fontan circulations, might derive additional benefit as the completely passive nature of blood flow through these circulations relies on low intrathoracic pressure.

The resuscitation outcomes of our cohort of patients receiving AC-CPR are overall similar to those of the larger ICU-RESUS cohort of surgical cardiac patients who underwent S-CPR, although the small numbers preclude adjusting for potential confounders.[28] The rate of ROSC > 20 min was 73% in our cohort of AC-CPR patients, and 64% in the cohort of surgical cardiac patients who underwent S-CPR. Among our patients, 18% transitioned to ECMO support vs. 28% in the larger group. Most importantly, survival rates in our cohort (55% overall, with favorable neurologic outcome 55%) were comparable to those of the larger ICU-RESUS surgical cardiac group (60% overall, with favorable neurologic outcome 58%). Additionally, AC-CPR allowed for uninterrupted compressions through emergent surgical intervention (i.e., chest opening, ECMO cannulation). This ability to maintain a high CCF through a surgical procedure may expedite the necessary intervention while avoiding prolonged periods without compressions. Given these outcomes and potential advantages, AC-CPR may prove useful even among non-cardiac patients undergoing ECPR or other critical interventions.

The main theoretical drawbacks to AC-CPR arise from the same mechanism that improves venous return: compression of the abdominal contents. The high abdominal pressures generated with adequate AC-CPR, particularly in the setting of low, or no cardiac output, could predispose to abdominal ischemia and organ dysfunction. In our cohort, only one patient who survived their arrest developed NEC within 24 h. A second patient developed NEC more than a month afterwards, which was unlikely connected to their arrest event. Evaluation for abdominal injury following resuscitation with only abdominal compressions was not standardized, and thus occult injury may have occurred that was not clinically apparent to the team following resuscitation.

While this case series serves as an initial step toward more well-developed clinical studies, there are several limitations. The patients in this cohort represent a critically ill group of infants with congenital heart disease with a median STAT category of 4 (range 3–5) (Table 1). Charts were reviewed for possible abdominal complications, but a systematic assessment of potential complications related to AC-CPR was not undertaken. While most of the patients in this cohort had invasive arterial monitoring above the level of the diaphragm (6 with radial arterial lines, 2 with umbilical arterial catheters, and one with both), there were 2 patients with femoral arterial access. Although the systolic, or compression, phase arterial pressures measured below the abdominal compression point may not accurately reflect simultaneous aortic pressures, the diastolic, or relaxation, phase should allow prompt equilibration of pressures above and below. Thus, we presume these DBPs during CPR reflect excellent coronary perfusion pressures and blood flows, and this presumption is supported by the high rate of sustained ROSC. Perhaps

Table 3 – Event hemodynamics over the first 10 min.

	Overall (N = 11)
Average diastolic blood pressure during abdominal compressions (mmHg)	
Median [Q1, Q3]	32 [23, 43]
Mean ± SD	34 ± 11.4
Min – Max	19–57
Average systolic blood pressure during abdominal compressions (mmHg)	
Median [Q1, Q3]	57 [48, 65]
Mean ± SD	57 ± 16.3
Min – Max	31–90
Average compression rate (per minute)	
Median [Q1, Q3]	114 [100, 124]
Mean ± SD	114 ± 16.9
Min – Max	84–142
Average compression fraction	
Median [Q1, Q3]	0.98 [0.93, 0.99]
Mean ± SD	0.94 ± 0.098
Min – Max	0.68–1.00
Average end-tidal CO_2 (mmHg)	
Median [Q1, Q3]	13.3 [11.5, 25.6]
Mean ± SD	18.0 ± 7.37
Min – Max	10.7–27.3
Average ventilation rate (breaths/min)	
Median [Q1, Q3]	22.0 [14.9, 24.8]
Mean ± SD	20.8 ± 6.27
Min – Max	11.8–29.1
Average CVP / RAP	
Median [Q1, Q3]	12.2 [8.6, 26.9]
Mean ± SD	19.6 ± 17.60
Min – Max	5.4–55.9
Mean CoPP[1]	
Median [Q1, Q3]	12.6 [3.3, 20.4]
Mean ± SD	13.1 ± 10.40
Min – Max	1.2–30.8

[1] CoPP: Coronary perfusion pressure; calculated from diastolic blood pressure and minimum diastolic central venous pressure or right atrial pressure.

Table 4 – Summary of outcomes.

	AC-CPR Cohort (N = 11)	ICU-RESUS Cohort (N = 383)
Survival to hospital discharge	6 (55%)	231 (60.4%)
Survival to hospital discharge with favorable neurologic outcome[1]	6 (55%)	222 (58%)
Total FSS at hospital discharge	7 [6,8]	
PCPC at hospital discharge		
1 – Normal	1 (9%)	
2 – Mild disability	4 (36%)	
3 – Moderate disability	1 (9%)	
4 – Severe disability	0 (0%)	
5 – Coma/vegetative state	0 (0%)	
6 – Death	5 (45%)	
Change from baseline to hospital discharge in functional status (FSS) of survivors	1 [0, 2]	
New morbidity[2] (survivors only)	1 (17%)	
Immediate outcome of CPR event		
ROSC $\geq$ 20 minutes[3]	8 (73%)	247 (64%)
Transitioned to ECMO	2 (18%)	
Died	1 (9%)	26 (7%)

FSS = Functional Status Scale; PCPC = Pediatric Cerebral Performance Category.

[1] Favorable neurologic outcome is defined as no more than moderate disability or no worsening from baseline Pediatric Cerebral Performance Category (PCPC).

[2] New morbidity among survivors is defined as a worsening from baseline FSS by 3 points or more.

[3] ROSC > 20 min: Return of spontaneous circulation after CPR for a period of time greater than 20 min.

the greatest obstacle to generalizability to a broader pediatric population is the highly controlled environment in which these events occurred, namely a pediatric cardiothoracic intensive care unit at a quaternary care center with a highly trained staff. Moreover, all patients had invasive and non-invasive monitors in place to allow real-time assessment of hemodynamics and surrogate markers of cardiac output such as end-tidal CO_2 monitoring and arterial blood pressure. This real-time physiologic data allowed for instantaneous modification of resuscitation procedures to ensure target markers were maintained. This strong focus on physiologic parameters may have impacted the outcome of resuscitative efforts and is not possible outside of an intensive care unit setting.[16]

Conclusions

Based on the preliminary data obtained from this series of patients, AC-CPR provided excellent hemodynamic and resuscitation metrics. While generalization to other areas of acute care in pediatrics is not possible, in the realm of pediatric cardiac intensive care, AC-CPR may offer a safe alternative to S-CPR for some of the most critically ill patients who are at high-risk for injury from external chest compressions. Larger randomized and controlled studies will be necessary to better characterize the applicability, efficacy, and outcomes of this resuscitation modality in the cardiac intensive care unit and beyond.

CRediT authorship contribution statement

Richard P. Fernandez: Writing – original draft, Investigation, Conceptualization. **Patrick I. McConnell:** Writing – review & editing, Conceptualization. **Ron W. Reeder:** Writing – review & editing, Methodology, Formal analysis. **Jessica S. Alvey:** Writing – review & editing, Methodology, Formal analysis. **Robert A. Berg:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Kathleen L. Meert:** Writing – review & editing. **Ryan W. Morgan:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Vinay M Nadkarni:** Writing – review & editing, Formal analysis, Conceptualization. **Heather A. Wolfe:** Writing – review & editing. **Robert M. Sutton:** Writing – review & editing, Resources, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrew R. Yates:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Richard P. Fernandez, MD reports financial support, administrative support, and statistical analysis were provided by National Institute of Child Health and Human Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resplu.2024.100765.

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REFERENCES

1. Webb RT, Bacon D. History of resuscitation. Int Anesthesiol Clin 2017;55:117–29.
2. 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.
3. Christenson J, Andrusiek D, Everson-Stewart S, et al. Chest compression fraction determines survival in patients with out-of-hospital ventricular fibrillation. Circulation 2009;120:1241–7.
4. Sutton RM, Reeder RW, Landis W, et al. Chest compression rates and pediatric in-hospital cardiac arrest survival outcomes. Resuscitation 2018;130:159–66.
5. Maher KO, Berg RA, Lindsey CW, Simsic J, Mahle WT. Depth of sternal compression and intra-arterial blood pressure during CPR in infants following cardiac surgery. Resuscitation 2009;80:662–4.
6. Sutton RM, Wolfe H, Nishisaki A, et al. Pushing harder, pushing faster, minimizing interruptions... but falling short of 2010

cardiopulmonary resuscitation targets during in-hospital pediatric and adolescent resuscitation. Resuscitation 2013;84:1680–4.
7. Martinez PA, Totapally BR. The epidemiology and outcomes of pediatric in-hospital cardiopulmonary arrest in the United States during 1997 to 2012. Resuscitation 2016;105:177–81.
8. Lowry AW, Knudson JD, Cabrera AG, Graves DE, Morales DL, Rossano JW. Cardiopulmonary resuscitation in hospitalized children with cardiovascular disease: estimated prevalence and outcomes from the kids' inpatient database. Pediatr Crit Care Med 2013;14:248–55.
9. Gupta P, Tang X, Gall CM, Lauer C, Rice TB, Wetzel RC. Epidemiology and outcomes of in-hospital cardiac arrest in critically ill children across hospitals of varied center volume: a multi-center analysis. Resuscitation 2014;85:1473–9.
10. Marino BS, Tabbutt S, MacLaren G, et al. Cardiopulmonary Resuscitation in Infants and Children With Cardiac Disease: A Scientific Statement From the American Heart Association. Circulation 2018;137:e691–782.
11. Park JB, Song IK, Lee JH, Kim EH, Kim HS, Kim JT. Optimal chest compression position for patients with a single ventricle during cardiopulmonary resuscitation. Pediatr Crit Care Med 2016;17:303–6.
12. Lowry AW. Resuscitation and perioperative management of the high-risk single ventricle patient: first-stage palliation. Congenit Heart Dis 2012;7:466–78.
13. Dunning J, Fabbri A, Kolh PH, et al. Guideline for resuscitation in cardiac arrest after cardiac surgery. Eur J Cardiothorac Surg 2009;36:3–28.
14. Society of Thoracic Surgeons Task Force on Resuscitation After Cardiac S. The Society of Thoracic Surgeons Expert Consensus for the Resuscitation of Patients Who Arrest After Cardiac Surgery. Ann Thorac Surg 2017;103:1005–20.
15. Icu R, Eunice Kennedy Shriver National Institute of Child H, Human Development Collaborative Pediatric Critical Care Research Network Investigator G, et al. Effect of Physiologic Point-of-Care Cardiopulmonary Resuscitation Training on Survival With Favorable Neurologic Outcome in Cardiac Arrest in Pediatric ICUs: A Randomized Clinical Trial. JAMA 2022;327:934–45.
16. Nolan JP, Berg RA, Andersen LW, et al. Cardiac arrest and cardiopulmonary resuscitation outcome reports: update of the Utstein resuscitation registry template for in-hospital cardiac arrest: a consensus report from a task force of the international liaison committee on resuscitation (American heart association, European resuscitation council, Australian and new Zealand council on resuscitation, heart and stroke foundation of Canada, InterAmerican heart foundation, resuscitation council of southern africa, resuscitation council of Asia). Circulation 2019;140:e746–57.
17. Pollack MM, Holubkov R, Glass P, et al. Functional Status Scale: new pediatric outcome measure. Pediatrics 2009;124:e18–28.
18. Jacobs I, Nadkarni V, Bahr J, et al. Cardiac arrest and cardiopulmonary resuscitation outcome reports: update and simplification of the Utstein templates for resuscitation registries: a statement for healthcare professionals from a task force of the international liaison committee on resuscitation (American Heart Association, European Resuscitation Council, Australian Resuscitation Council, New Zealand Resuscitation Council, Heart and Stroke Foundation of Canada, InterAmerican Heart Foundation, Resuscitation Councils of Southern Africa). Circulation 2004;110:3385–97.
19. Becker LB, Aufderheide TP, Geocadin RG, et al. Primary outcomes for resuscitation science studies: a consensus statement from the American Heart Association. Circulation 2011;124:2158–77.
20. Ortmann L, Prodhan P, Gossett J, et al. Outcomes after in-hospital cardiac arrest in children with cardiac disease: a report from get with the guidelines-resuscitation. Circulation 2011;124:2329–37.
21. 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.
22. Berg RA, Sutton RM, Reeder RW, et al. Association between diastolic blood pressure during pediatric in-hospital cardiopulmonary resuscitation and survival. Circulation 2018;137:1784–95.
23. Berg RA, Morgan RW, Reeder RW, et al. Diastolic blood pressure threshold during pediatric cardiopulmonary resuscitation and survival outcomes: a multicenter validation study. Crit Care Med 2023;51:91–102.
24. Berg RA, Reeder RW, Meert KL, et al. End-tidal carbon dioxide during pediatric in-hospital cardiopulmonary resuscitation. Resuscitation 2018;133:173–9.
25. Morgan RW, Berg RA, Reeder RW, et al. The physiologic response to epinephrine and pediatric cardiopulmonary resuscitation outcomes. Crit Care 2023;27:105.
26. Yates AR, Sutton RM, Reeder RW, et al. Survival and cardiopulmonary resuscitation hemodynamics following cardiac arrest in children with surgical compared to medical heart disease. Pediatr Crit Care Med 2019;20:1126–36.
27. 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.
28. Federman M, Sutton RM, Reeder RW, et al. Survival with favorable neurologic outcome and quality of cardiopulmonary resuscitation following in-hospital cardiac arrest in children with cardiac disease compared with noncardiac disease. Pediatr Crit Care Med 2023.
29. Ralston SHBC, Niebauer MJ. Cardiopulmonary resuscitation with interposed abdominal compression in dogs. Anesth Analg 1982;61:645–51.
30. Sack JB, Kesselbrenner MB, Jarrad A. Interposed abdominal compression-cardiopulmonary resuscitation and resuscitation outcome during asystole and electromechanical dissociation. Circulation 1992;86:1692–700.
31. Georgiou MPE, Middleton N, Papalois A, Xanthos T. Combination of chest compressions and interposed abdominal compressions in a swine model of ventricular fibrillation. Am J Emerg Med 2016;34:968–74.
32. Geddes LA, Rundell A, Lottes A, Kemeny A, Otlewski M. A new cardiopulmonary resuscitation method using only rhythmic abdominal compression: a preliminary report. Am J Emerg Med 2007;25:786–90.
33. Pargett M, Geddes LA, Otlewski MP, Rundell AE. Rhythmic abdominal compression CPR ventilates without supplemental breaths and provides effective blood circulation. Resuscitation 2008;79:460–7.
34. Lottes AE, Rundell AE, Geddes LA, Kemeny AE, Otlewski MP, Babbs CF. Sustained abdominal compression during CPR raises coronary perfusion pressures as much as vasopressor drugs. Resuscitation 2007;75:515–24.