Survival and Cardiopulmonary Resuscitation Hemodynamics Following Cardiac Arrest in Children With Surgical Compared to Medical Heart Disease*

Andrew R. Yates, MD[1]; Robert M. Sutton, MD, MSCE[2]; Ron W. Reeder, PhD[3]; Kathleen L. Meert, MD[4]; John T. Berger, MD[5]; Richard Fernandez, MD[1]; David Wessel, MD[5]; Christopher J. Newth, MD[6]; Joseph A. Carcillo, MD[7]; Patrick S. McQuillen, MD[8]; Rick E. Harrison, MD[9]; Frank W. Moler, MD[10]; Murray M. Pollack, MD[5,11]; Todd C. Carpenter, MD[12]; Daniel A. Notterman, MD[13]; J. Michael Dean, MD[3]; Vinay M. Nadkarni, MD, MS[2]; Robert A. Berg, MD[2]; and the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development Collaborative Pediatric Critical Care Research Network

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[1]Department of Pediatrics, Nationwide Children's Hospital, The Ohio State University, Columbus, OH.

[2]Department of Anesthesiology and Critical Care Medicine, The Children's Hospital of Philadelphia, University of Pennsylvania, Philadelphia, PA.

[3]Department of Pediatrics, University of Utah, Salt Lake City, UT.

[4]Department of Pediatrics, Children's Hospital of Michigan, Wayne State University, Detroit, MI.

[5]Department of Pediatrics, Children's National Medical Center, Washington, DC.

[6]Department of Anesthesiology and Critical Care Medicine, Children's Hospital Los Angeles, University of Southern California Keck College of Medicine, Los Angeles, CA.

[7]Department of Critical Care Medicine, Children's Hospital of Pittsburgh, University of Pittsburgh, Pittsburgh, PA.

[8]Department of Pediatrics, Benioff Children's Hospital, University of California San Francisco, San Francisco, CA.

[9]Department of Pediatrics, Mattel Children's Hospital, University of California Los Angeles, Los Angeles, CA.

[10]Department of Pediatrics, C.S. Mott Children's Hospital, University of Michigan, Ann Arbor, MI.

[11]Department of Pediatrics, Phoenix Children's Hospital, Phoenix, AZ.

[12]Department of Pediatrics, Denver Children's Hospital, University of Colorado, Denver, CO.

[13]Department of Molecular Biology, Princeton University, Princeton, NJ.

A complete list of *Eunice Kennedy Shriver* National Institute of Child Health and Human Development Collaborative Pediatric Critical Care Research Network members are listed in the *Acknowledgments* section.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website (http://journals.lww.com/pccmjournal).

Supported, in part, by the following cooperative agreements from the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development, National Institutes of Health, Department of Health and Human Services: UG1HD050096, UG1HD049981, UG1HD049983, UG1HD063108, UG1HD083171, UG1HD083166, UG1HD083170, U10HD050012, U10HD063106, U10HD063114, and U01HD049934.

Drs. Yates's, Berger's, Newth's, and Carcillo's institutions received funding from the National Institutes of Child Health and Human Development. Drs. Yates, Reeder, Meert, Berger, Wessel, Newth, Carcillo, McQuillen, Harrison, Moler, Pollack, Carpenter, Dean, Nadkarni, and Berg received support for article research from the National Institutes of Health (NIH). Dr. Sutton's institution received funding from National Heart, Lung, and Blood Institute R01 to study cardiopulmonary resuscitation quality improvement bundle; he received funding from Zoll Medical (speaking honoraria); and he disclosed he is a volunteer for the American Heart Association (AHA), is the Chair for AHA's Get with the Guidelines Resuscitation Pediatric Research Task Force, and was an author for the 2015 and 2018 Pediatric Advanced Life Support Guidelines. Drs. Reeder's, Meert's, Wessel's, Harrison's, Moler's, Pollack's, Dean's, and Berg's institutions received funding from the NIH. Dr. Berger's institution received funding from Association for Pediatric Pulmonary Hypertension and Actelion Pharmaceutical. Dr. Newth received funding from Philips Research North America. The remaining authors have disclosed that they do not have any potential conflicts of interest.

For information regarding this article, E-mail: Andrew.yates@nationwidechildrens.org

DOI: 10.1097/PCC.0000000000002088

Objectives: To assess the association of diastolic blood pressure cutoffs (≥ 25 mm Hg in infants and ≥ 30 mm Hg in children) during cardiopulmonary resuscitation with return of spontaneous circulation and survival in surgical cardiac versus medical cardiac patients. Secondarily, we assessed whether these diastolic blood pressure targets were feasible to achieve and associated with outcome in physiology unique to congenital heart disease (single ventricle infants, open chest), and influenced outcomes when extracorporeal cardiopulmonary resuscitation was deployed.

Design: Multicenter, prospective, observational cohort analysis.

Setting: Tertiary PICU and cardiac ICUs within the Collaborative Pediatric Critical Care Research Network.

Patients: Patients with invasive arterial catheters during cardiopulmonary resuscitation and surgical cardiac or medical cardiac illness category.

Interventions: None.

Measurements and Main Results: Hemodynamic waveforms during cardiopulmonary resuscitation were analyzed on 113 patients, 88 surgical cardiac and 25 medical cardiac. A similar percent of surgical cardiac (51/88; 58%) and medical cardiac (17/25; 68%) patients reached the diastolic blood pressure targets ($p = 0.488$). Achievement of diastolic blood pressure target was associated with improved survival to hospital discharge in surgical cardiac patients ($p = 0.018$), but not medical cardiac patients ($p = 0.359$). Fifty-three percent (16/30) of patients with single ventricles attained the target diastolic blood pressure. In patients with an open chest at the start of chest compressions, 11 of 20 (55%) attained the target diastolic blood pressure. In the 33 extracorporeal cardiopulmonary resuscitation patients, 16 patients (48%) met the diastolic blood pressure target with no difference between survivors and nonsurvivors ($p = 0.296$).

Conclusions: During resuscitation in an ICU, with invasive monitoring in place, diastolic blood pressure targets of greater than or equal to 25 mm Hg in infants and greater than or equal to 30 mm Hg in children can be achieved in patients with both surgical and medical heart disease. Achievement of diastolic blood pressure target was associated with improved survival to hospital discharge in surgical cardiac patients, but not medical cardiac patients. Diastolic blood pressure targets were feasible to achieve in 1) single ventricle patients, 2) open chest physiology, and 3) extracorporeal cardiopulmonary resuscitation patients. (*Pediatr Crit Care Med* 2019; 20:1126–1136)

Key Words: cardiac; cardiopulmonary resuscitation; congenital heart disease; pediatric

Pediatric patients with surgical and medical heart disease have a 10-fold higher rate of in-hospital cardiac arrest than pediatric patients without heart disease (1). Observational studies consistently demonstrate higher rates of survival to hospital discharge in patients with surgical cardiac disease compared with medical cardiac disease (1–4). The surgical cardiac patients in these studies were more likely to have arterial access, prearrest tracheal intubation, and central vascular access at the time of arrest compared with the medical cardiac patients (3). Because they were more highly monitored, it is possible that observed survival difference between these groups was due to quality of cardiopulmonary resuscitation (CPR).

A recent American Heart Association (AHA) scientific statement on resuscitation of infants and children with heart disease has supported utilizing standard pediatric CPR techniques (chest compression rate of 100–120 per minute, chest compression fraction [CCF] > 0.8, ventilation rate of 10 breaths/min), with guidance from arterial and central venous pressure monitoring devices to help direct resuscitation (5). It is unknown whether the use of standard CPR techniques in pediatric patients with heart disease can result in arterial diastolic blood pressure (DBP) targets of greater than or equal to 25 mm Hg for infants and greater than or equal to 30 mm Hg for children, hemodynamic parameters previously associated with survival (6–9). Children with heart disease may have alterations in cardiac anatomy and physiology, such as single ventricle physiology and the presence of an open chest that may impede achievement of these hemodynamic resuscitation goals. Many single ventricle infants are palliated with a systemic to pulmonary artery shunt, which results in holodiastolic runoff into the pulmonary vascular bed and may complicate achievement of DBP goals (5, 10). The presence of an open chest in postoperative patients may facilitate circumferential open cardiac massage, but could also impair cardiac output when the sternum is open and compressions are performed on the patch or chest wall without circumferential open cardiac massage (11–13). Other factors unique to this patient population, such as selection for extracorporeal cardiopulmonary resuscitation (eCPR), may provide an additional survival benefit for patients who do not achieve return of spontaneous circulation (ROSC) (4, 5, 14–17).

The Pediatric Intensive Care Quality of Cardiopulmonary Resuscitation (PICqCPR) study evaluated children with invasive hemodynamic data during the first 10 minutes of CPR, including children with heart disease (6). PICqCPR demonstrated that mean DBP greater than or equal to 25 mm Hg during CPR in infants and greater than or equal to 30 mm Hg in children greater than or equal to 1 year old was associated with greater likelihood of survival to hospital discharge with favorable neurologic outcome. We thus hypothesized that achieving DBP targets of greater than or equal to 25 mm Hg in infants and greater than or equal to 30 mm Hg in children would be associated with ROSC and survival to discharge in the subsets of children with surgical and medical cardiac diseases. We also assessed whether arterial blood pressure targets were achievable in patients with single ventricle physiology and open chest physiology and whether CPR hemodynamics were associated with survival in patients who underwent eCPR.

MATERIAL AND METHODS

Setting and Design

The *Eunice Kennedy Shriver* National Institute of Child Health and Human Development Collaborative Pediatric Critical Care Research Network (CPCCRN) conducted the PICqCPR study between July 2013 and June 2016. PICqCPR was a prospective, observational study approved with waiver of informed consent by the Institutional Review Board at each clinical site and the data coordination center. All children in a PICU/cardiac ICU within CPCCRN and with an invasive arterial blood pressure monitoring line prior to and during CPR who received chest compressions for at least 1 minute were eligible for inclusion if greater than or equal to 37 weeks gestation and less than 19 years old. Subjects were excluded if the first compression was not captured on the waveform data or compression starts and stops could not be determined.

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, resuscitation interventions, and outcome data including Pediatric Cerebral Performance Category (PCPC) and Functional Status Scale (FSS) (18). Survival to hospital discharge with a favorable neurologic outcome was defined as PCPC 1–3 or no worse than prearrest PCPC, as per recommended guidelines (19, 20). The illness categories included in this analysis were categorized as either surgical cardiac or medical cardiac using definitions from the AHA "Get with the Guidelines-Resuscitation." 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

The first 10 minutes of hemodynamic data were collected for each CPR event. Data extraction methodology has previously been published for systolic, diastolic, and mean blood pressure (6), chest compression rate and fraction (22), ventilation rate, and end-tidal CO_2 analysis (23).

Statistical Analysis

Patient and event characteristics were summarized using frequencies and percentages or medians and interquartile ranges. Differences in these characteristics between surgical cardiac and medical cardiac admission categories were examined using Fisher exact test for categorical variables and the Wilcoxon rank-sum test for continuous variables. Event-level averages were used for outcome analyses. *p* values are reported based on a two-sided alternative and considered statistically significant when less than 0.05.

A compression rate of 100–120 per minute was considered to be compliant with AHA Guideline recommendations (7). Guideline recommendation for CCF of 0.80 and ventilation rate of 10 breaths per minute were used (7, 9). Patient admission categories were analyzed for achievement of hemodynamic targets associated with improved survival, specifically for DBP target of greater than or equal to 25 mm Hg for infants or greater than or equal to 30 mm Hg for children (5–7, 9, 24–26).

RESULTS

A total of 164 patients were enrolled in the PICqCPR cohort with analyzable events. Of these, 88 patients (54%) had an admission diagnosis category of surgical cardiac and 25 (15%) were designated as medical cardiac patients. Patient characteristics are outlined in **Table 1**. Surgical cardiac patients tended to be younger ($p < 0.001$) and more likely to have congenital heart disease (CHD) ($p < 0.001$) than medical cardiac patients. Surgical cardiac patients were less likely to have preexisting renal insufficiency than medical cardiac patients (5/88, 6% vs 7/25, 28%; $p = 0.004$). For patients with CHD, the only anatomic diagnosis data available was for patients with hypoplastic left heart syndrome (HLHS) as outlined in Table 1.

The surgical cardiac and medical cardiac patient groups were both highly instrumented as demonstrated by similar prevalence of vascular access, arterial catheters, vasoactive infusions, and respiratory support (**Supplemental Table 1**, Supplemental Digital Content 1, http://links.lww.com/PCC/B55). Supplemental Table 1 (Supplemental Digital Content 1, http://links.lww.com/PCC/B55) also contains data on immediate cause of arrest, time category of arrest (day, night, or weekend), initial cardiac rhythm, duration of CPR, and pharmacologic interventions. Hypotension was present in greater than 50% of patients in both categories prior to arrest. Hemodynamics achieved during the first 10 minutes of CPR (**Table 2**) demonstrated lower systolic, diastolic, and mean blood pressure in surgical cardiac patients than medical cardiac patients. The two groups did not differ in the rate of achievement of DBP goals (DBP ≥ 25 mm Hg for infants and DBP ≥ 30 mm Hg for children): 51 of 88 (58%) among surgical cardiac versus 17 of 25 (68%) among medical cardiac patients ($p = 0.488$).

Surgical cardiac and medical cardiac patients had no difference in the achievement of ROSC for greater than or equal to 20 minutes (59/88, 67% vs 15/25, 60%; $p = 0.634$) but surgical cardiac patients had greater survival to hospital discharge compared with medical cardiac patients (49/88, 56% vs 8/25, 32%; $p = 0.043$). All surgical cardiac patients either achieved ROSC for greater than or equal to 20 minutes (59/88, 67%) or underwent eCPR (29/88, 33%), whereas only four of 10 (40%) medical cardiac patients without ROSC for greater than or equal to 20 minutes were cannulated for eCPR. Surgical and medical cardiac patients that survived had similar rates of favorable neurologic outcome based on PCPC scores (45/49, 92% vs 8/8, 100%; $p = 1.000$).

Achievement of a DBP target of greater than or equal to 25 mm Hg for infants or greater than or equal to 30 mm Hg for children was associated with improved survival to hospital discharge in surgical cardiac patients (34/49 [69%] vs 17/39 [44%]; $p = 0.018$), but not in medical cardiac patients (4/8 [50%] vs 13/17 [77%]; $p = 0.359$). As shown in **Tables 3** and **4**, performance of CPR within AHA resuscitation guideline targets was not associated with achievement of ROSC or survival to hospital discharge.

HLHS (31/113; 27%) was the only diagnosis used to classify patients as a single ventricle (**Table 5**). In palliated single ventricle patients, 16 of 30 (53%) attained the target DBP of greater than or equal to 25 mm Hg for infants or greater than or equal to 30 mm Hg for children. The median DBP achieved during the first 10 minutes of CPR was nearly identical in HLHS patients with either a Norwood with modified Blalock-Taussig (MBT) shunt or a Norwood with right ventricle to pulmonary artery (RVPA) shunt. The MBT group was more likely to survive to hospital discharge than the RVPA group (8/9, 89% vs 3/8, 38%; $p = 0.05$).

As noted in **Table 6**, 20 patients in the surgical cardiac cohort had an open chest at the start of chest compressions, and 11 of 20 (55%) attained the target DBP of greater than or equal to 25 mm Hg for infants or greater than or equal to

TABLE 1. Patient Characteristics by Cardiac Illness Category

Variable	Overall ($n = 113$)	Illness Category: Surgical Cardiac ($n = 88$)	Illness Category: Medical Cardiac ($n = 25$)	*p*
Age category, *n* (%)				< 0.001[a]
< 1 mo	38 (33.6)	37 (42.0)	1 (4.0)	
1 mo to < 1 yr	39 (34.5)	32 (36.4)	7 (28.0)	
1 yr to < 8 yr	23 (20.4)	13 (14.8)	10 (40.0)	
8 yr to < 19 yr	13 (11.5)	6 (6.8)	7 (28.0)	
Sex, *n* (%)				0.063[a]
Male	69 (61.1)	58 (65.9)	11 (44.0)	
Female	44 (38.9)	30 (34.1)	14 (56.0)	
Race, *n* (%)				0.139[a]
White	58 (51.3)	47 (53.4)	11 (44.0)	
Black or African American	22 (19.5)	13 (14.8)	9 (36.0)	
Other	4 (3.5)	3 (3.4)	1 (4.0)	
Unknown or not reported	29 (25.7)	25 (28.4)	4 (16.0)	
Preexisting conditions, *n* (%)				
Respiratory insufficiency	86 (76.1)	66 (75.0)	20 (80.0)	0.792[a]
Hypotension	88 (77.9)	70 (79.5)	18 (72.0)	0.424[a]
Congestive heart failure	18 (15.9)	11 (12.5)	7 (28.0)	0.117[a]
Pneumonia	4 (3.5)	3 (3.4)	1 (4.0)	1.000[a]
Sepsis	19 (16.8)	16 (18.2)	3 (12.0)	0.559[a]
Renal insufficiency	12 (10.6)	5 (5.7)	7 (28.0)	0.004[a]
Malignancy	2 (1.8)	1 (1.1)	1 (4.0)	0.395[a]
Congenital heart disease	89 (78.8)	77 (87.5)	12 (48.0)	< 0.001[a]
HLHS, *n* (%)	31 (27.4)	27 (30.7)	4 (16.0)	1.000[a]
HLHS anatomy, $n = 31$, *n* (%)				0.743[a]
Preoperative	1 (3.2)	1 (3.7)	0 (0.0)	
Norwood with modified Blalock-Taussig shunt	9 (29.0)	7 (25.9)	2 (50.0)	
Norwood with right ventricle to pulmonary artery shunt	8 (25.8)	8 (29.6)	0 (0.0)	
Hybrid procedure	2 (6.5)	2 (7.4)	0 (0.0)	
Bidirectional Glenn (Hemi-Fontan)	6 (19.4)	5 (18.5)	1 (25.0)	
Fontan	5 (16.1)	4 (14.8)	1 (25.0)	
Baseline Pediatric Cerebral Performance Category score, *n* (%)				0.997[b]
1—Normal	54 (47.8)	42 (47.7)	12 (48.0)	
2—Mild disability	35 (31.0)	28 (31.8)	7 (28.0)	
3—Moderate disability	14 (12.4)	9 (10.2)	5 (20.0)	
4—Severe disability	8 (7.1)	7 (8.0)	1 (4.0)	
5—Coma/vegetative state	2 (1.8)	2 (2.3)	0 (0.0)	
Baseline total Functional Status Scale, median (interquartile range)	8 (6–10)	8 (6–12)	6 (6–8)	0.026[b]

HLHS = hypoplastic left heart syndrome.
[a]Fisher exact test.
[b]Wilcoxon rank-sum test.

TABLE 2. Event Characteristics by Cardiac Illness Category

Variable	Overall (*n* = 113)	Illness Category: Surgical Cardiac (*n* = 88)	Illness Category: Medical Cardiac (*n* = 25)	*p*
Average over (up to) the first 10 min				
Chest compression rate (/min)	127.1 (114.5–139.2)	128.4 (113.9–140.2)	122.7 (117.5–129.8)	0.217[a]
DBP (mm Hg)	27.7 (22.0–36.5)	26.4 (21.9–34.8)	33.0 (27.4–42.0)	0.031[a]
DBP (mm Hg) ≥ 25 for infants or ≥ 30 for children, *n* (%)	68 (60.2)	51 (58.0)	17 (68.0)	0.488[b]
SBP (mm Hg)	69.3 (53.0–93.2)	66.3 (50.9–87.6)	79.0 (67.6–100.0)	0.037[a]
SBP (mm Hg) ≥ 60 for infants or ≥ 80 for children, *n* (%)	61 (54.0)	47 (53.4)	14 (56.0)	1.000[b]
Mean arterial pressure (mm Hg)	43.0 (33.9–54.5)	42.5 (33.0–50.7)	48.3 (38.7–60.7)	0.023[a]
Ventilation rate (/min)[c]	32.7 (24.9–37.4)	34.9 (30.2–48.4)	24.9 (20.2–33.1)	0.043[a]
End-tidal CO_2 (mm Hg)[c]	15.8 (9.4–25.2)	10.9 (8.7–20.5)	24.7 (16.4–26.3)	0.149[a]
Chest compression fraction	0.9 (0.8–1.0)	0.9 (0.8–1.0)	0.9 (0.8–0.9)	0.507[a]
Outcomes, *n* (%)				
Return of spontaneous circulation ≥ 20 min	74 (65.5)	59 (67.0)	15 (60.0)	0.634[b]
Return of circulation with extracorporeal cardiopulmonary resuscitation	33 (29.2)	29 (33.0)	4 (16.0)	0.136[b]
Survival to hospital discharge	57 (50.4)	49 (55.7)	8 (32.0)	0.043[b]
Neurologic outcomes in survivors (*n* = 57)				
Favorable neurologic outcome based on PCPC[d], *n* (%)	53 (93.0)	45 (91.8)	8 (100.0)	1.000[b]
PCPC at hospital discharge, *n* (%)				0.080[a]
Normal	21 (36.8)	20 (40.8)	1 (12.5)	
Mild disability	21 (36.8)	18 (36.7)	3 (37.5)	
Moderate disability	10 (17.5)	7 (14.3)	3 (37.5)	
Severe disability	5 (8.8)	4 (8.2)	1 (12.5)	
Total FSS score at hospital discharge	8.0 (8.0–12.0)	8.0 (8.0–12.0)	11.0 (9.5–11.5)	0.095[a]
Change from baseline to hospital discharge total FSS	0.0 (−1.0 to 3.0)	0.0 (−1.0 to 2.0)	2.5 (1.0–4.0)	0.140[a]
New morbidity at hospital discharge[e], *n* (%)	16 (28.1)	12 (24.5)	4 (50.0)	0.202[b]

DBP = diastolic blood pressure, FSS = Functional Status Scale, PCPC = Pediatric Cerebral Performance Category, SBP = systolic blood pressure.
[a]Wilcoxon rank-sum test. Continuous variables are summarized using median (Q1–Q3).
[b]Fisher exact test.
[c]Ventilation rate and end-tidal CO_2 data were available for *n* = 20 total subjects (*n* = 14 surgical cardiac, *n* = 6 medical cardiac).
[d]Favorable neurologic outcome defined as discharge PCPC of normal, mild disability, or moderate disability or a discharge PCPC no worse than baseline PCPC.
[e]New morbidity defined as an increase of at least three between baseline and discharge FSS.

30 mm Hg for children. The open chest patients tended to be younger ($p = 0.008$) and more often required eCPR compared with the cardiac patients without an open chest (10/20 [50%] vs 23/93 [24.7%], $p = 0.032$). Average systolic blood pressure (SBP), DBP, and achievement of a DBP target of greater than or equal to 25 mm Hg for infants or greater than or equal to 30 mm Hg for children during the first 10 minutes of CPR was no different in those patients with an open chest compared with those without an open chest. The chest was opened during the course of CPR in an additional five of 70 (7.1%) surgical patients.

Of the 33 eCPR patients, 16 patients (48%) met the DBP target. In children who underwent cannulation for eCPR, neither the average DBP during CPR nor the frequency of achieving the DBP targets differed between survivors and non-survivors to hospital discharge (**Table 7**).

TABLE 3. Resuscitation Guidelines by Cardiac Illness Category and Survival to Hospital Discharge

Variable	Surgical Cardiac: Status at Hospital Discharge			Medical Cardiac: Status at Hospital Discharge		
	Dead ($n = 39$)	Alive ($n = 49$)	p	Dead ($n = 17$)	Alive ($n = 8$)	p
Compression rate in guidelines (100–120 per min), n (%)	15 (38.5)	12 (24.5)	0.172[a]	7 (41.2)	3 (37.5)	1.000[a]
Diastolic blood pressure (mm Hg) ≥ 25 for infants or ≥ 30 for children, n (%)	17 (43.6)	34 (69.4)	0.018[a]	13 (76.5)	4 (50.0)	0.359[a]
Systolic blood pressure (mm Hg) ≥ 60 for infants or ≥ 80 for children, n (%)	18 (46.2)	29 (59.2)	0.283[a]	9 (52.9)	5 (62.5)	1.000[a]
Ventilation rate[b] (/min), median (interquartile range)	34.7 (26.7–49.4)	34.9 (30.2–48.4)	0.944[c]	24.7 (20.2–33.1)	25.1 (25.1–25.1)	1.000[c]
$etco_2$ < 10 (mm Hg)[b], n (%)	2 (50.0)	2 (20.0)	0.520[a]	1 (20.0)	0 (0.0)	1.000[a]
$etco_2$ ≥ 20 (mm Hg)[b], n (%)	0 (0.0)	4 (40.0)	0.251[a]	3 (60.0)	1 (100.0)	1.000[a]
Chest compression fraction ≥ 90%, n (%)	22 (56.4)	25 (51.0)	0.829[a]	10 (58.8)	3 (37.5)	0.411[a]

$etco_2$ = end-tidal CO_2.
[a]Fisher exact test.
[b]Ventilation rate and $etco_2$ data were not available for all cardiac subjects ($n = 14$ surgical cardiac, $n = 6$ medical cardiac).
[c]Wilcoxon rank-sum test.

TABLE 4. Resuscitation Guidelines by Cardiac Illness Category and Return of Spontaneous Circulation

Variable	Surgical Cardiac: ROSC ≥ 20 min			Medical Cardiac: ROSC ≥ 20 min		
	No ($n = 29$)	Yes ($n = 59$)	p	No ($n = 10$)	Yes ($n = 15$)	p
Compression rate in guidelines (100–120 per min), n (%)	14 (48.3)	13 (22.0)	0.015[a]	3 (30.0)	7 (46.7)	0.678[a]
Diastolic blood pressure (mm Hg) ≥ 25 for infants or ≥ 30 for children, n (%)	13 (44.8)	38 (64.4)	0.108[a]	6 (60.0)	11 (73.3)	0.667[a]
Ventilation rate[b] (/min), median (interquartile range)	48.8 (35.9–61.7)	33.0 (29.4–43.1)	0.235[c]	24.7 (20.2–34.1)	25.1 (19.9–33.1)	1.000[c]
$etco_2$ < 10 (mm Hg)[b], n (%)	1 (3.4)	3 (5.1)	0.505[a]	1 (10.0)	0 (0.0)	1.000[a]
$etco_2$ ≥ 20 (mm Hg)[b], n (%)	1 (3.4)	3 (5.1)	0.505[a]	1 (10.0)	3 (20.0)	0.400[a]
Chest compression fraction ≥ 90%, n (%)	16 (55.2)	31 (52.5)	1.000[a]	6 (60.0)	7 (46.7)	0.688[a]

$etco_2$ = end-tidal CO_2, ROSC = return of spontaneous circulation.
[a]Fisher exact test.
[b]Ventilation rate and $etco_2$ data were not available for all cardiac subjects ($n = 14$ surgical cardiac, $n = 6$ medical cardiac).
[c]Wilcoxon rank-sum test.

DISCUSSION

These PICqCPR data establish that invasive DBP targets during CPR greater than or equal to 25mm Hg in infants and greater than or equal to 30 mm Hg in children were attained in 51 of 88 (58%) surgical cardiac and 17 of 25 (68%) medical cardiac patients. Importantly, surgical cardiac patients who attained these DBP targets during CPR were more likely to survive to hospital discharge. Additionally, these DBP targets were attained during CPR in 16 of 30 (53%) single ventricle patients and 11 of 20 (55%) open chest patients. Although both the chest compression rates and ventilation rates were not compliant with AHA guidelines for most of these children, 50%

TABLE 5. Event Characteristics and Outcomes in Hypoplastic Left Heart Syndrome Subjects

Variable	Hypoplastic Left Heart Syndrome Anatomy				
	Modified Blalock-Taussig Shunt ($n = 9$)	Right Ventricle to Pulmonary Artery Shunt ($n = 8$)	Hybrid ($n = 2$)	Cavopulmonary Anastamosis ($n = 11$)	Other Congenital Heart Disease ($n = 58$)
Average over (up to) the first 10 min[a]					
Chest compression rate (/min)	141.1 (109.7–143.1)	119.7 (112.7–132.4)	132.0 (121.0–143.0)	125.3 (118.4–155.9)	128.3 (114.0–139.6)
DBP (mm Hg)	25.0 (20.0–33.3)	23.6 (22.8–27.8)	27.3 (18.6–36.0)	33.0 (24.0–49.1)	28.0 (22.9–36.1)
DBP (mm Hg) ≥ 25 for infants or ≥ 30 for children, *n* (%)	5 (55.6)	3 (37.5)	1 (50.0)	7 (63.6)	38 (65.5)
SBP (mm Hg)[b]	67.6 (49.0–74.5)	93.9 (64.6–102.0)	47.6 (26.2–69.0)	68.0 (48.7–83.0)	67.6 (55.0–90.0)
SBP (mm Hg) ≥ 60 for infants or ≥ 80 for children[c], *n* (%)	6 (66.7)	6 (75.0)	1 (50.0)	5 (45.5)	31 (53.4)
Mean arterial pressure (mm Hg)	39.2 (29.7–47.0)	44.7 (37.5–51.4)	34.1 (21.1–47.0)	42.5 (34.5–67.0)	42.9 (35.2–53.0)
Chest compression fraction	0.86 (0.85–0.92)	0.95 (0.87–0.96)	0.75 (0.73–0.77)	0.93 (0.88–0.98)	0.90 (0.84–0.96)
Outcomes, *n* (%)					
Return of spontaneous circulation ≥ 20 min	5 (55.6)	5 (62.5)	1 (50.0)	10 (90.9)	41 (70.7)
Return of circulation with extracorporeal cardiopulmonary resuscitation	4 (44.4)	3 (37.5)	1 (50.0)	1 (9.1)	15 (25.9)
Survival to hospital discharge[d]	8 (88.9)	3 (37.5)	1 (50.0)	6 (54.5)	30 (51.7)

DBP = diastolic blood pressure, SBP = systolic blood pressure.

[a]Continuous variables are summarized using median (Q1–Q3).

[b]Average SBP was not significantly different between modified Blalock-Taussig (MBT) shunt and right ventricle to pulmonary artery (RVPA) shunt subjects ($p = 0.075$, Wilcoxon rank-sum test).

[c]Rate of SBP target achievement was not significantly different between MBT shunt and RVPA shunt subjects ($p = 1.000$, Fisher exact test).

[d]Survival to hospital discharge was significantly different between MBT shunt and RVPA shunt subjects ($p = 0.050$, Fisher exact test).

survived to hospital discharge and favorable neurologic outcome occurred in 93% of the survivors. The significant survival benefit when DBP targets are met, despite deviations from AHA guidelines, suggests reevaluation of chest compression rates and ventilation rates is warranted.

The recent AHA statement on the resuscitation of infants and children with heart disease highlights the lack of data available to provide specific hemodynamic targets to guide resuscitation (5). Our data support targeting DBP goals of greater than or equal to 25 mm Hg for infants and greater than or equal to 30 mm Hg for children post cardiac surgery, consistent with the data for the overall PICqCPR population (7). However, it is not known if the optimal targets are different in that our smaller sample size did not allow for evaluation of alternative target goals.

Interestingly, surgical cardiac patients had a higher rate of survival to discharge than medical cardiac patients, despite similar rates of achievement of DBP targets (58% surgical and 68% medical), and similar rates of ROSC (67% of surgical and 60% of medical patients). Presumably, surgical cardiac patients had acute, reversible physiologic derangements (e.g., post-pump cardiomyopathy), whereas medical cardiac patients may have had less reversible processes. In other words, successful CPR could provide surgical cardiac patients a bridge to survival, whereas medical cardiac patients may have had more limited potential to survive despite excellent CPR and successful ROSC. Recognition of high risk of mortality, either perceived or actual, may have contributed to lower overall use of eCPR in medical cardiac patients (33% surgical cardiac vs 16% medical cardiac).

Single ventricle patients have the highest frequency, and lowest survival, of cardiac arrest of all pediatric patients with heart disease (1, 27, 28). Not surprisingly, the single ventricle population was a large percentage of the PICqCPR cardiac patients (31/113, 27%). These data establish that a DBP of greater than or equal to 25 mm Hg in an infant with a MBT

TABLE 6. Comparison of Cardiac Subjects With Open Versus Closed Chest at Start of Cardiopulmonary Resuscitation

Variable	Open Chest at Start of Cardiopulmonary Resuscitation No (*n* = 93)	Yes (*n* = 20)	*p*
Age category, *n* (%)			0.008[a]
< 1 mo	25 (26.9)	13 (65.0)	
1 mo to < 1 yr	37 (39.8)	2 (10.0)	
1 yr to < 8 yr	20 (21.5)	3 (15.0)	
8 yr to < 19 yr	11 (11.8)	2 (10.0)	
Sex, *n* (%)			0.453[a]
Male	55 (59.1)	14 (70.0)	
Female	38 (40.9)	6 (30.0)	
Average DBP (mm Hg), median (IQR)	29.0 (22.7–38.4)	25.7 (17.9–32.4)	0.080[b]
Average DBP (mm Hg) ≥ 25 for infants or ≥ 30 for children, *n* (%)	57 (61.3)	11 (55.0)	0.622[a]
Average SBP (mm Hg)[4], median (IQR)	69.3 (53.0–93.2)	70.0 (53.1–91.0)	0.931[b]
Average SBP (mm Hg) ≥ 60 for infants or ≥ 80 for children, *n* (%)	49 (52.7)	12 (60.0)	0.626[a]
Return of spontaneous circulation ≥ 20 min, *n* (%)	64 (68.8)	10 (50.0)	0.125[a]
Return of circulation with extracorporeal cardiopulmonary resuscitation, *n* (%)	23 (24.7)	10 (50.0)	0.032[a]
Survival to hospital discharge, *n* (%)	48 (51.6)	9 (45.0)	0.630[a]

DBP = diastolic blood pressure, IQR = interquartile range, SBP = systolic blood pressure.
[a]Fisher exact test.
[b]Wilcoxon rank-sum test.

shunt is an achievable hemodynamic target. There was very little difference in the DBP achieved in HLHS with MBT shunt compared with the RVPA shunt. Our data suggest a higher survival rate after CPR following Norwood with MBT shunt compared with Norwood with RVPA, in contrast to a previous single-center study (27). Interestingly, multicenter data found a higher frequency of CPR in MBT shunted patients compared with RVPA patients, with no difference in overall 30-day survival, which may similarly suggest improved survival following CPR in MBT shunted patients compared with RVPA (28).

A second unique patient cohort was 20 of 113 (18%) pediatric cardiac patients with open chest. There is limited published data on open chest CPR in pediatric patients (29). Current knowledge of resuscitation physiology with an open chest is primarily related to animal studies which reported improvement in ROSC and survival with circumferential open cardiac massage compared with closed-chest compressions (.12, 13, 30) The PICqCPR study did not specifically collect data on which method of compressions was performed (i.e., circumferential open cardiac massage, focal compressions on the patch with an open chest, abdominal CPR, vs some combination) precluding comments on ideal technique. Regardless, current practice in PICqCPR units resulted in similar SBP, DBP, and achievement of age-specific SBP and DBP targets during resuscitation with an open chest as in those patients with a closed chest. Not surprisingly, 50% of open chest patients underwent cannulation for eCPR as higher surgical complexity is one indication for leaving the chest open following surgery. A recent Society of Thoracic Surgeons guideline for postoperative cardiac arrest in adults recognized that resternotomy was common (20–50% of patients) during arrest and recommended early sternal opening within 5 minutes (26). However, our data would suggest a lower rate of chest opening in pediatric surgical cardiac patients, as only five of 70 (7%) in this PICqCPR series had resternotomy despite a median duration of CPR of 11 minutes. This rate may be influenced by enrollment bias and by a greater percentage of postoperative open chest in the pediatric patient cohort but may be an intervention requiring further study.

The most recent AHA guideline statement also recommended early deployment of eCPR for the resuscitation of patients with CHD. Thirty-three of 113 cardiac patients (29%) obtained return of circulation (ROC) with eCPR. Interestingly, all surgical cardiac patients achieved ROSC or ROC with eCPR. Our data demonstrated 39.4% survival to hospital discharge, consistent with reports of 20–50% survival in the

TABLE 7. Event Characteristics and Outcomes in Extracorporeal Cardiopulmonary Resuscitation Patients

Variable	Vital Status at Hospital Discharge		p
	Dead ($n = 20$)	Alive ($n = 13$)	
Age category, n (%)			0.184[a]
< 1 mo	7 (35.0)	9 (69.2)	
1 mo to < 1 yr	5 (25.0)	3 (23.1)	
1 yr to < 8 yr	5 (25.0)	1 (7.7)	
8 yr to < 19 yr	3 (15.0)	0 (0.0)	
Sex, n (%)			0.087[a]
Male	9 (45.0)	10 (76.9)	
Female	11 (55.0)	3 (23.1)	
Duration of CPR (min), median (IQR)	48.5 (38.5–55.5)	28.0 (16.0–52.0)	0.109[b]
CPR time category, n (%)			0.284[a]
Weekday	9 (45.0)	9 (69.2)	
Weeknight/weekend	11 (55.0)	4 (30.8)	
Illness category, n (%)			0.136[a]
Surgical cardiac	16 (80.0)	13 (100.0)	
Medical cardiac	4 (20.0)	0 (0.0)	
Pharmacologic interventions			
Epinephrine, n (%)	19 (95.0)	13 (100.0)	1.000[a]
Total number of epi doses, median (IQR)	5.0 (3.0–9.0)	4.0 (3.0–5.0)	0.599[b]
Calcium, n (%)	11 (55.0)	10 (76.9)	0.278[a]
Sodium bicarbonate, n (%)	17 (85.0)	11 (84.6)	1.000[a]
Average DBP (mm Hg), median (IQR)	23.5 (16.1–29.4)	26.6 (23.0–32.0)	0.204[b]
Average DBP (mm Hg) ≥ 25 for infants or ≥ 30 for children, n (%)	8 (40.0)	8 (61.5)	0.296[a]
Average SBP (mm Hg), median (IQR)	55.1 (48.3–80.8)	83.7 (64.0–98.2)	0.156[b]
Average SBP (mm Hg) ≥ 60 for infants or ≥ 80 for children, n (%)	7 (35.0)	10 (76.9)	0.032[a]

CPR = cardiopulmonary resuscitation, DBP = diastolic blood pressure, IQR = interquartile range, SBP = systolic blood pressure.
[a]Fisher exact test.
[b]Wilcoxon rank-sum test.

pediatric cardiac eCPR population (14, 16, 17). A recently published study found that DBP during CPR was no different in a small number of eCPR patients compared with conventional CPR, similar to our data (31). However, we have also demonstrated that attaining DBP targets for age was not associated with improved survival in our patients undergoing eCPR. SBP may better reflect "stroke volume" during CPR and thereby flows to noncardiac organs (e.g., brain and kidney). This may be more important in eCPR than conventional CPR as the duration of CPR prior to cannulation is longer, and thus maintaining adequate organ perfusion ultimately improves survival. The selection bias and high utilization of eCPR may impact the increased survival in the surgical cardiac patient population compared with medical cardiac patients.

The PICqCPR dataset has several limitations in that patients were selected based on presence of invasive arterial catheters and adequate waveforms for blood pressure analysis. Although the relevance of these DBP data may not be generalizable to patients without an invasive arterial catheter, it is precisely these patients with an invasive arterial catheter for whom we can titrate our CPR and advanced life support to attain a DBP hemodynamic target. Hemodynamic data were only collected for the first 10 minutes of CPR (or less when CPR duration was < 10 min), thereby precluding assessment of the entire CPR period when the duration of CPR was greater than 10 minutes. The PICqCPR database did not specify cardiac diagnosis other than HLHS, and thus does not differentiate patients who may have had shunt physiology, elevated end-diastolic pressures, or other regurgitant lesions which may influence hemodynamics (e.g., severe aortic regurgitation). It is also unknown whether the shunt was found to be obstructed in the HLHS patients with MBT shunts. Additionally, the medical cardiac and HLHS patient groups constituted small sample sizes for comparisons. Although some central venous or right atrial pressure tracings were submitted for analysis, frequent interruptions for medication administration prevented adequate estimates of coronary perfusion pressure.

CONCLUSIONS

These PICqCPR data demonstrate that during resuscitation in an ICU with invasive monitoring, DBP targets of greater than or equal to 25 mm Hg in infants and greater than or equal to 30 mm Hg in children can be achieved in most patients with both surgical and medical heart disease, and attaining these target DBPs was associated with higher rates of survival to hospital discharge among cardiac surgical patients. Additionally, these DBP targets could be achieved during CPR among most children with single ventricle physiology and most children with open chest physiology.

ACKNOWLEDGMENTS

We acknowledge the contributions of the following researchers, research coordinators, and data coordinating center staff of the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development Collaborative Pediatric Critical Care Research Network: Richard Holubkov, PhD, Chris Locandro, MS, Russell Telford, MS, Whitney Coleman, Alecia Peterson, MS, and Julie Thelen from the University of Utah, Salt Lake City, UT; Athena F. Zuppa, MD, MSCE, Katherine Graham, BS, Carolann Twelves, RN, and Mary Ann Diliberto, RN, from The Children's Hospital of Philadelphia, Philadelphia, PA; Elyse Tomanio, RN, from Children's National Medical Center, Washington, DC; Jeni Kwok, JD, from University of Southern California Keck College of Medicine, Los Angeles, CA; Michael J. Bell, MD, and Alan Abraham, MBA, from Children's Hospital of Pittsburgh, Pittsburgh, PA; Anil Sapru, MD, and Mustafa F. Alkhouli, BA, from Benioff Children's Hospital, San Francisco, CA; Sabrina Heidemann, MD, and Ann Pawluszka, RN, from Children's Hospital of Michigan, Detroit, MI; Mark W. Hall, MD, and Lisa Steele, RN, from Nationwide Children's Hospital, Columbus, OH; Thomas P. Shanley, MD, and Monica Weber, RN, from C.S. Mott Children's Hospital, Ann Arbor, MI; Heidi J. Dalton, MD, and Aimee La Bell, RN, from Phoenix Children's Hospital, Phoenix, AZ; Peter M. Mourani, MD, and Kathryn Malone, RN, from Denver Children's Hospital, Denver, CO; and Allan Doctor, MD, from Washington University School of Medicine, St. Louis, MO. We also acknowledge the contribution of Tammara L. Jenkins, MSN, RN, and Robert F. Tamburro, MD, from *Eunice Kennedy Shriver* National Institute of Child Health and Human Development, Bethesda, MD.

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