Characterization of Pediatric In-Hospital Cardiopulmonary Resuscitation Quality Metrics Across an International Resuscitation Collaborative

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A full list of the pediatric Resuscitation Quality (pediRES-Q) Collaborative Investigators are listed in **Appendix 1**.

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Objectives: Pediatric in-hospital cardiac arrest cardiopulmonary resuscitation quality metrics have been reported in few children less than 8 years. Our objective was to characterize chest compression fraction, rate, depth, and compliance with 2015 American Heart Association guidelines across multiple pediatric hospitals.

Design: Retrospective observational study of data from a multicenter resuscitation quality collaborative from October 2015 to April 2017.

Setting: Twelve pediatric hospitals across United States, Canada, and Europe.

Patients: In-hospital cardiac arrest patients (age < 18 yr) with quantitative cardiopulmonary resuscitation data recordings.

Interventions: None.

Measurements and Main Results: There were 112 events yielding 2,046 evaluable 60-second epochs of cardiopulmonary resuscitation (196,669 chest compression). Event cardiopulmonary resuscitation metric summaries (median [interquartile range]) by age: less than 1 year (38/112): chest compression fraction 0.88 (0.61–0.98), chest compression rate 119/min (110–129), and chest compression depth 2.3 cm (1.9–3.0 cm); for 1 to less than 8 years (42/112): chest compression fraction 0.94 (0.79–1.00), chest compression rate 117/min (110–124), and chest compression depth 3.8 cm (2.9–4.6 cm); for 8 to less than 18 years (32/112): chest compression fraction 0.94 (0.85–1.00), chest compression rate 117/min (110–123), chest compression depth 5.5 cm (4.0–6.5 cm). "Compliance" with guideline targets for 60-second chest compression "epochs" was predefined: chest compression fraction greater than 0.80, chest compression rate 100–120/min, and chest compression depth: greater than or equal to 3.4 cm in less than 1 year, greater than or equal to 4.4 cm in 1 to less than 8 years, and 4.5 to less than 6.6 cm in 8 to less than 18 years. Proportion of less than 1 year, 1 to less than 8 years, and 8 to less than 18 years events with greater than or equal to 60% of 60-second epochs meeting compliance (respectively): chest compression fraction was 53%, 81%, and 78%; chest compression rate was 32%, 50%, and 63%; chest compression depth was 13%, 19%, and 44%. For all events combined, total compliance (meeting all three guideline targets) was 10% (11/112).

Conclusions: Across an international pediatric resuscitation collaborative, we characterized the landscape of pediatric in-hospital cardiac arrest chest compression quality metrics and found that they often do not meet 2015 American Heart Association guidelines. Guideline compliance for rate and depth in children less than 18 years is poor, with the greatest difficulty in achieving chest compression depth targets in younger children. (*Pediatr Crit Care Med* 2018; XX:00–00)

Key Words: cardiopulmonary resuscitation; chest compressions; children; collaborative; pediatric; quality

Cardiac arrest occurs in 2–6% of children admitted to a PICU which is approximately 100-fold higher than out-of-hospital arrest (1–4). Over the last 15 years, there have been substantial improvements in survival outcomes after pediatric in-hospital cardiac arrest (IHCA) (5), but cardiopulmonary resuscitation (CPR) quality is largely unmeasured, and there are many children who suffer neurologic sequelae. As previous investigations have associated CPR quality with cardiac arrest outcome (6, 7), implementation of programs targeted to monitor and improve resuscitation quality is warranted.

Pediatric CPR guidelines have been developed with data often extrapolated from adult and animal investigations (8). Most of what we know about pediatric Resuscitation Quality (pediRES-Q) comes from single-center in-hospital investigations (7, 9–12). Feasibility to capture CPR quality metrics has been previously demonstrated in a single quaternary center and established that CPR quality in older children and adolescents frequently does not achieve American Heart Association (AHA) Pediatric Basic Life Support (BLS) quality targets (9, 11, 13). However, the landscape of CPR quality for children across multiple pediatric hospitals has not been reported or analyzed, and extrapolation of CPR performance at a single center may not be generalizable. Thus, there is a need for larger pediatric studies that can describe resuscitation practice. Recently, technology to quantitatively evaluate CPR quality in younger children age 0 to less than 8 years has received U.S. Food and Drug Administration clearance, allowing a knowledge gap in the field of pediatric resuscitation science to be studied.

Using a multicenter pediRES-Q improvement collaborative, the objective of this project was to characterize CPR metrics (chest compression [CC] fraction, CC rate, CC depth, CC release velocity [CCRV]) and compliance with 2015 AHA guideline targets for children less than 18 years old. We expected that the CPR performed in these children would often not achieve AHA Guideline targets for CC fraction (CCF), CC rate, and CC depth.

MATERIALS AND METHODS

Design and Setting

This was a convenience sample of data collected from the pediRES-Q Collaborative (ClinicalTrials.gov: NCT02708134). The pediRES-Q Collaborative is a large, multicenter international pediRES-Q improvement network (Appendix 1, Supplemental Digital Content 1, http://links.lww.com/PCC/A633). The study was approved by local institutional review boards (United States) or research ethics boards (Europe and Canada) and met criteria for a waiver of consent per Code of Federal Regulations 45 CFR 46.116(d) and 45 CFR 46.408(a) (https://www.hhs.gov/ohrp/regulations-and-policy/regulations/45-cfr-46/index.html - 46.116). An additional Data Use Agreement was obtained per local institutional regulations. Strict compliance with the HIPAA to ensure patient confidentiality was maintained at all times.

Population

This study includes cardiac arrest patients from hospitals participating in the pediRES-Q collaborative. A convenience sample of IHCA events (that were entered in the collaborative database) in children less than 18 years old who received CCs greater than or equal to 1-minute duration with capture of evaluable CPR quality metric data (as described below) were included.

Data Collection

A data collection form with 100 data elements was created which aligns with the AHA's Get with the Guidelines-Resuscitation cardiopulmonary arrest patient management tool (http://www.heart.org/idc/groups/heart-public/@private/@wcm/@hcm/@gwtg/documents/downloadable/ucm_457481.pdf). Data on each resuscitation event were collected by a site investigator or research staff. Research staffs at each site designated to perform data entry were required to complete an 1-hour training session by the Data Coordinating Center (DCC, Children's Hospital of Philadelphia) consisting of a one-on-one live webinar prior to database access. Data were entered into and managed using Research Electronic Data Capture electronic data capture tools coordinated and hosted at The Children's Hospital of Philadelphia under an agreement with the software's development consortium, led by Vanderbilt University. Finally, once entered, each event record went through a manual review by the DCC in order to be approved and added to the dataset.

CC metrics were measured and recorded during resuscitations with a monitor-defibrillator (R-series; ZOLL Medical, Chelmsford, MA) with Food and Drug Administration–cleared accelerometer-based technology. CC metric data included CCF, CC rate (CC/min), CC depth (cm), and CCRV (mm/s). Release velocity is a quantitative measurement of the maximum chest recoil velocity during decompression. The accelerometer technology is integrated into defibrillator pads that are used for patient monitoring and defibrillation. These dual sensor pads require anterior-posterior placement to record actual CC depth and eliminate artifact due to mattress deflection (14–16). Any event that deployed anterior apical placement of electrode pads was excluded from analysis. Application of the "pediatric" electrode pads (for children 0–8 yr or < 25 kg) enables display of compression rate and depth measurements on the defibrillator screen. Application of the "adult" electrode pads (> 8 yr or ≥ 25 kg) enables display of compression rate and depth measurements "and" corrective voice prompts and visual indicators of CPR performance for adult target depth on the display. Corrective voice prompts and visual indication of CPR performance "are not" enabled with use of the "pediatric" electrodes due to the guidelines not recommending a specific depth for the 0–8-year-old age range.

CC Metrics

Epochs were defined as 60-second segments during which CPR was ongoing, beginning with the first measured compression after placement of electrode pads as captured by the monitor-defibrillator. CCF was defined as the percentage of time compressions performed during CPR. Pauses in CC for interventions such as ventilation, defibrillation, or tracheal intubation were not edited or excluded. "Continuous" compressions were defined as at least five back-to-back compressions with a duration interval between compressions of less than 1 second. When evaluating epochs, we were not confident that all accelerometer depths of less than 1.5 cm were true CC; thus, these potential artifacts were manually excluded from analysis. A sensitivity analysis was conducted including all CC, including those less than 1.5 cm (Appendix 2, Supplemental Digital Content 2, http://links.lww.com/PCC/A634). Furthermore, accelerometer depths of greater than 8 cm were identified and considered artifact so were also manually excluded. In order to characterize CCs that were within depth range, we a priori included CCs within ± 10% AHA guideline target depth (as defined below) for each age group. CC rate was characterized using the mean CC rate (CC/min), and chest recoil was characterized by the median CCRV (mm/s) achieved during each 60-second epoch of CCs, as calculated and reported by the ZOLL RescueNet Code Review software. For each 60-second epoch, the CCF, median CC rate (CC/min), and median CC depth (cm) were calculated and reported.

Compliance With Resuscitation Guideline Targets

Recommendations from the 2013 AHA CPR Quality Consensus Statement and the 2015 AHA BLS guidelines were used to define AHA compliance for CCF (greater than 0.80), CC rate (100–120 CC/min), and CC depth targets for both analyses (8, 13). In children under the age of 8 years, guidelines recommend a CC depth at least one-third diameter of chest or about 4.0 cm for infants less than 1 year or about 5.0 cm for children 1 to less than 8 years. Guidelines recommend a CC depth between 5.0 and 6.0 cm for children 8 to less than 18 years. Thus, for our primary analysis, we defined relative CC depth target to approximately one-third anterior-posterior chest depth (APD) for children under the age of 8 years based on previously published literature as at least 3.4 cm for infants less than 1 year and at least 4.4 cm (17–19) for children 1 to less than 8 years and for children 8 to less than 18 year as 4.5–6.6 cm (± 10% guideline depth). In an additional alternative sensitivity analysis, we applied absolute CC depth criteria (± 10% guideline depth) for infants less than 1 year as 3.6–4.4 cm, for children 1 to less than 8 years as 4.5–5.5 cm.

We evaluated each 60-second epoch for compliance with AHA CPR quality target ranges (8, 13) for 1) CCF, 2) median CC rate, and 3) median CC depths (as defined above). The following definitions were used to describe additional compliance variables: 4) combinations of two measures meeting criteria: CCF and CC rate (7, 20, 21), CCF and CC depth, and CC rate and CC depth and 5) all three measures, CCF, CC rate, and CC depth meeting criteria. "Event" compliance was defined as a cardiac arrest event with 60% or more of its 60-second epochs meeting each of the criteria, as described above (20).

Analysis

Cardiac arrest events were excluded if CPR began outside the hospital, had incomplete data collection (i.e., event within last month or patient not yet discharged), or did not have CPR metric data. Additionally, any events that reported single sensor pads (i.e., no compensation for depth of mattress compression), anterior apical placement of the dual sensor pads, or inaccurate placement of dual sensor pads (data accuracy of misaligned pads unable to be confirmed) were also excluded from analysis. Likewise, we excluded events where all the CC data were less than 1.5 cm or greater than 8 cm depth, as these depths are likely artefactual based upon improper CC sensor placement (as described above). As recommended by the Utstein reporting guidelines, we define survival with favorable neurologic outcome at hospital discharge as a Pediatric Cerebral Performance Category (PCPC) score of 1–3 or no change in PCPC from the patient's baseline (prearrest) status (22, 23).

RescueNet Code Review v5.71 (ZOLL Medical, Chelmsford, MA) was used to export event CC data. Data from each event contained CC time, CC rate, CC depth, and CCRV. These data were individually analyzed using a custom application developed using C# (Microsoft, Redmond, WA). This application was used to generate event feedback data reports, epoch data, and aggregated release velocities used in analysis.

Standard descriptive statistics were used to summarize patient demographics, event and hospital characteristics, and the quality of CPR performed during the cardiac arrest event. Summary results for CCF, CC rate, CC depth, and CCRV are presented as the median and interquartile range (IQR). CCF was reported as a fraction. For the primary analysis, proportions of 60-second epochs and events meeting compliance with AHA quality CPR targets (± 10% for depth) were reported as frequencies (percentages) unless indicated. chi-square analysis was used to compare differences in compliance among age groups.

RESULTS

Between October 2015 and April 2017, 155 pediatric CPR events for subjects less than 18 years old were entered into the pediRES-Q database. Of those, 112 events from 12 hospitals (range, 1–21 events/site) had complete data necessary for analyses (**Fig. 1**). The 112 events yielded 2,118 60-second epochs of CPR, of which only 36 epochs (1.7%) with an average depth of less than 1.5 cm were excluded. There were no significant differences in median depths between all epochs with and those without the less than 1.5 cm CCs for the entire cohort nor when evaluated by age category (Appendix 3, Supplemental Digital Content 3, http://links.lww.com/PCC/A635). Data analysis was completed on the remaining 2,046 60-second epochs of CPR (196,669 CC). **Table 1** displays demographics for patients and distribution by age. For all events, median age was 2.3 years (IQR, 0.6–9.5 yr), and 57% were male.

Table 2 displays characteristics of patient events. The majority of the analyzed events occurred in a critical care setting (85%), and 58% of events occurred on a weekday between 07:00 and 22:59. The most frequent immediate cause of arrest was hypoxia/respiratory decompensation (54%) followed by hypotension/hypoperfusion (46%). It was reported in 62% of events that the defibrillator electrodes/pads (with sensor) were not in place at time of first CC (median minutes of CCs prior to pad placement: 3 min [IQR, 1–6 min]). Upon initiation of CCs, 46% of the patients (52/112) were documented to have poor perfusion with a palpable pulse. For those without a documented pulse at the initiation of CCs (54% [60/112]), pulseless electrical activity was reported in 57% (34/60). Over the course of the resuscitation event, 21% of the patients (24/112) required defibrillation (12 with initial ventricular fibrillation [VF]/ventricular tachycardia [VT] and 12 with subsequent VF/VT). Of those, 54% (13/24) required more than one shock. All 112 patients received epinephrine: 30% received two to four doses, and 58% received five or more doses. Median time to first epinephrine dose was 2.0 minutes (IQR, 0–3.0 min) after the first documented CC (Table 2).

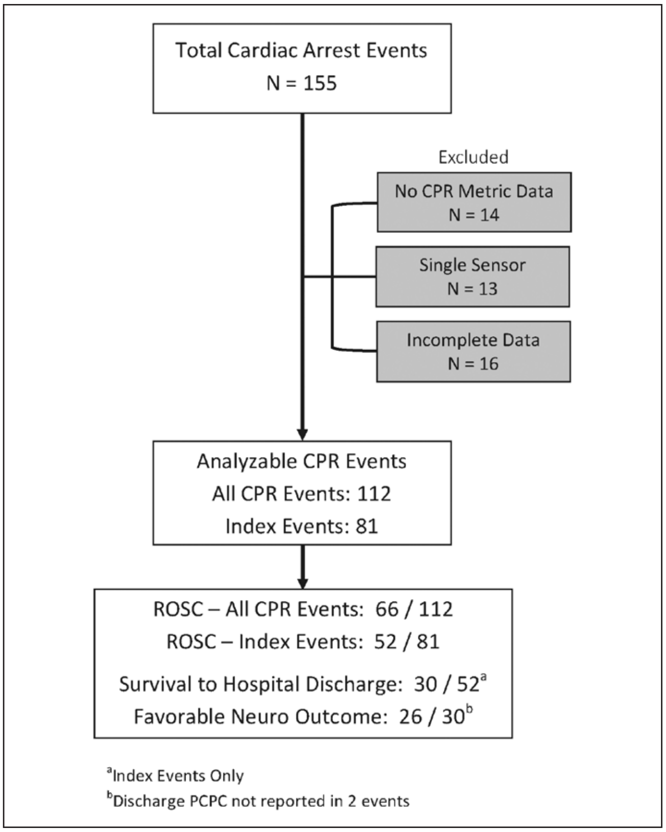

Figure 1. Utstein style consort diagram. CPR = cardiopulmonary resuscitation, PCPC = Pediatric Cerebral Performance Category, ROSC = return of a sustained circulation.

Of the 112 resuscitation events, 72% (81/112) were index (first in-hospital CPR event for current admission) events. Return of a sustained circulation (ROSC) was achieved in 59% of all events (66/112) (10 with extracorporeal membrane oxygenation [ECMO] CPR rescue) and in 64% of index events (52/81) (eight with ECMO CPR rescue). Of the 52 index events that achieved ROSC, 58% (30/52) survived to ICU discharge, of which 100% also survived to hospital discharge. Eighty-seven percent of survivors (26/30) had a documented favorable neurologic outcome at their hospital discharge (two survivors did not have PCPC scores documented) (Table 2).

CPR Metrics

Table 3 summarizes CC metrics and compliance for the three age categories. Median CCF was 0.88 in less than 1 year and 0.94 in both 1 to less than 8 years and 8 to less than 18 years. Median depth was 2.3 cm in less than 1 year, 3.8 cm in 1 to less than 8 years, and 5.5 cm in 8 to less than 18 years. Median release velocities increased as age category increased: 147 mm/s, 217 mm/s, and 366 mm/s, respectively.

CPR 60-Second Epochs: Compliance With Resuscitation Guidelines

Table 3 displays the results from the evaluation of each "60-second epoch" for compliance with AHA-derived target

TABLE 1. Patient Demographics by Age

Demographics	All	< 1 yr	1 to < 8 yr	8 to < 18 yr
n (%)	112 (100)	38 (34)	42 (38)	32 (29)
Age, yr, median (IQR)	2.3 (0.6–9.5)	0.5 (0.2–0.6)	2.6 (1.8–5.3)	13.0 (10.6–15.1)
Gender, male, *n* (%)	64 (57)	22 (58)	25 (60)	17 (53)
Weight, kg, median (IQR)	11.7 (6.4–26.7)	5.5 (4.0–6.7)	13.3 (10.9–17.1)	45.1 (31.7–60.6)
Race, *n* (%)				
Black	32 (29)			
White	57 (51)			
Asian	6 (5)			
Other/not documented	17 (15)			
Illness category, *n* (%)				
Medical cardiac	17 (15)			
Medical noncardiac	59 (53)			
Surgical cardiac	25 (22)			
Surgical noncardiac	10 (9)			
Trauma	1 (1)			
Preexisting conditions ("may have > 1 at time of event"), *n* (%)				
Cardiac malformation	45 (40)			
Congenital malformation (noncardiac)	26 (23)			
Congestive heart failure	25 (22)			
Hypotension/hypoperfusion	44 (39)			
Metabolic/electrolyte abnormality	39 (35)			
Metastatic or hematologic malignancy	8 (7)			
Pneumonia	14 (13)			
Renal insufficiency	25 (22)			
Respiratory insufficiency	80 (71)			
Septicemia	12 (11)			

IQR = interquartile range.

ranges. CCF had the highest compliance for each age group, with 72% compliance for all ages combined. CC depth had the poorest compliance among all age groups: 17% for less than 1 year, 30% for 1 to less than 8 years, and 48% for those between 8 and less than 18 years; 31% for all ages combined. Compliance for a combination of two variables was highest in the 8 to less than 18 years group for CCF and CC rate (49%) and lowest in the less than 1 year old group for CC rate and CC depth (8%). Total guideline compliance (proportion of epochs meeting all three targets) was 5% for less than 1 year, 16% for 1 to less than 8 years, and 39% for 8 to less than 18 years. Using chi-square, there was a significant difference in AHA compliance for epochs by age: less than 1 year versus 1 to less than 8 years versus 8 to less than 18 years for all metrics ($p < 0.001$).

When applying the ± 10% guideline absolute CC depth target for those under the age of 8, CC depth compliance decreased to 8% for the less than 1-year events and total compliance decreased to 2%. Likewise, using the absolute depth target in 1 to less than 8-year events, we found that CC depth compliance decreased to 17% and total compliance decreased to 11%.

CPR Event: Compliance With Resuscitation Guidelines

Table 4 displays the event-level analysis of the proportion meeting AHA CPR quality targets. Those events where greater than or equal to 60% of 60-second epochs were compliant with AHA CPR quality targets were as follows: less than 1 year old: 53% CCF, 32% CC rate, and 13% for CC depth; 1 to less than

TABLE 2. Arrest Characteristics

Characteristics		n (%)
Location of arrest		
Cardiac ICU		21 (19)
Neonatal ICU		2 (2)
PICU		72 (64)
Theaters/recovery		3 (3)
Ward		6 (5)
Emergency department		9 (8)
Day of arrest	Time of arrest	
Weekday		
Day/evening	07:00 to 22:59	65 (58)
Night	23:00 to 06:59	20 (18)
Weekend		
Day/evening	07:00 to 22:59	15 (13)
Night	23:00 to 06:59	12 (11)
Interventions in place prior to arrest ("each patient may have > 1 intervention")		
Tracheal tube		80 (71)
Noninvasive ventilation		69 (62)
End-tidal CO_2 monitoring		77 (69)
Intraarterial catheter		45 (40)
Defibrillator electrodes/pads in place at time of first compression		
Yes		28 (25)
Unknown		15 (13)
Duration of chest compressions prior to pad placement (min), median (IQR)		3 (1–6)
Immediate cause of arrest		
Arrhythmia (VF, ventricular tachycardia, supraventricular tachycardia)		21 (19)
Hypotension/hypoperfusion		51 (46)
Hypoxia/respiratory decompensation		62 (54)
Rhythm at initiation of chest compressions		
Palpable pulse		52 (46)
Pulseless		60 (54)
Asystole		9 (15)
Pulseless electrical activity		34 (57)
VF/pulseless ventricular tachycardia		12 (20)
Unknown		5 (8)
Patients requiring defibrillation		
1 shock		11 (46)
> 1 shock		13 (54)

(*Continued*)

TABLE 2. (*Continued*). Arrest Characteristics

Characteristics	n (%)
Patients given epinephrine (10 μg/kg), dose	
1	13 (12)
2–4	34 (30)
≥ 5	65 (58)
Time to first epinephrine from start of compressions (min), median (IQR)	2 (0–3)
Outcomes	
Return of a sustained circulation	
Of all events (112)	66 (59)
Of index events (81)	52 (64)
Survival to ICU discharge	30 (58)
Survival to hospital discharge	30 (58)
Discharged with favorable neurologic outcome[a]	26 (87)

IQR = interquartile range, VF = ventricular fibrillation.
[a]Pediatric Cerebral Performance Category not reported for two events.

8 years old: 81% CCF, 50% CC rate, and 19% CC depth; and 8 to less than 18 years old: 78% CCF, 63% CC rate, and 44% for CC depth. Those events where greater than or equal to 60% of 60-second epochs were compliant with AHA CPR quality targets were as follows: less than 1 year: 53% CCF, 32% CC rate, and 13% CC depth; 1 to less than 8 years: 81% CCF, 50% CC rate, and 19% CC depth; and 8 to less than 18 years: 78% CCF, 63% CC rate, and 44% CC depth. The proportion of events with greater than or equal to 60% of epochs meeting a combination of two variables was highest in the 8 to less than 18 years events for CCF and CC rate targets (38%) and lowest in both the less than 1 year and 8 to less than 18 years events for CC rate and CC depth (5% each). Total guideline compliance (proportion of events with ≥ 60% of epochs meeting all three targets) were highest in the 8 to less than 18 years events (22%) and lowest in 1 to less than 8 years events (2%). When applying the ± 10% guideline absolute CC depth target for those under the age of 8, there was a decrease in compliance for the less than 1 year events (0%) but no change in the 1 to less than 8 years events (2%). Using chi-square, there was a significant difference between AHA metric compliance for events by age: less than 1 year versus 1 to less than 8 years versus 8 to less than 18 years in all metrics except for any under 8 years when using the ± 10% guideline absolute CC depth target ($p > 0.29$).

DISCUSSION

This contemporary (2015–2017) multicenter analysis fills an important gap in resuscitation knowledge by characterizing in-hospital CPR quality metrics for infants and children across a spectrum of 12 pediatric hospitals. FDA-cleared technology now makes it feasible to collect and record CPR quality metrics (CCF, CC rate, CC depth, and CCRV) during real

TABLE 3. Summaries of Cardiopulmonary Resuscitation 60-Second Epochs and Compliance With American Heart Association Metric Targets

	Total	< 1 yr	1 to < 8 yr	8 to < 18 yr	p
Events (*n*)	112	38	42	32	
CCs (*n*)	196,669	52,215	92,260	52,194	
60-s epochs (*n*)	2,046	592	936	518	
Epoch summaries, median (IQR)					
CC fraction (%)	93 (76–100)	88 (61–98)	94 (79–100)	94 (85–100)	
CC rate (CC/min)	117 (110–125)	119 (110–129)	117 (110–124)	117 (110–123)	
CC depth (cm)	3.6 (2.4–5.0)	2.3 (1.9–3.0)	3.8 (2.9–4.6)	5.5 (4.0–6.5)	
Maximum release velocity (mm/s)	217 (154–323)	147 (117–195)	217 (171–280)	366 (258–440)	
Epoch compliance, *n* (%)					
CC fraction	1,469 (72)	360 (61)	696 (74)	413 (80)	< 0.001
CC rate	1,130 (55)	271 (46)	543 (58)	316 (61)	< 0.001
CC depth[a,b]	635 (31)	103 (17)	286 (30)	246 (48)	< 0.001
Absolute[c]		49 (8)	163 (17)		< 0.001
CC fraction and CC rate	848 (42)	186 (31)	407 (44)	255 (49)	< 0.001
CC fraction and CC depth[a,b]	501 (25)	72 (12)	217(23)	212 (41)	< 0.001
Absolute[c]		37 (6)	137 (15)		< 0.001
CC rate and CC depth[a,b]	395 (19)	48 (8)	195 (21)	152 (29)	< 0.001
Absolute[c]		19 (3)	120 (13)		< 0.001
CC fraction, CC rate, and CC depth[a,b]	384 (19)	32 (5)	151 (16)	201 (39)	< 0.001
Absolute[c]		14 (2)	103 (11)		< 0.001

CC = chest compression, IQR = interquartile range.

[a]Using Guideline ≥ 1/3 Anterior-Posterior chest depth for < 8 yr: ≥ 3.4 cm for < 1 yr and ≥ 4.4 cm for 1 to < 8 yr.

[b]Using ± 10% Guideline absolute depth for 8 to < 18 yr is 4.5–6.6 cm.

[c]Using secondary ± 10% Guideline absolute depth for < 8 yr: 3.6–4.4 cm for < 1 yr and 4.5–5.5 cm for 1 to < 8 yr.

Differences in compliances analyzed using χ^2 analysis.

pediatric IHCA events. Our analysis of CPR metrics found that for all events, compliance with AHA CPR quality metric targets was relatively good for CCF (71% [79/112]) but poor for CC depth (24% [27/112]). Even with the application of prospectively set liberal definitions of "compliance" requiring only 60% of the CPR 60-second epochs to achieve AHA guideline targets (20), using the metrics with the highest compliance, CCF, and CC rate, only 28% of the events (31/112) simultaneously met both targets. Achieving compliance for all three AHA-derived CPR quality targets was extremely difficult with only 10% of all events (11/112) doing so, calling into question the ability to reach a combination of these three compliance targets in actual pediatric resuscitation. However, the objective of this study was to collect performance data generated without a unified structured approach to improve performance through the use of available CPR feedback information. Previous studies in adults have shown that CPR quality improves when feedback is combined with a structured training effort (24, 25).

Comparison to Prior Pediatric IHCA Reports

Similar to previous small single-center IHCA reports, healthcare providers had difficulty delivering CPR compliant AHA guidelines for CC rate and CC depth. In a previous characterization of the first 5 minutes of in-hospital CPR quality among only eight patients 1 to less than 8 years old and 70 patients 8 to less than 18 years old (7), the number of events compliant with 2010 AHA Guidelines was 91% for CCF, 70% for CC rate, and 26% for CC depth. Additionally, in a five-patient case series of video-recorded pediatric emergency department CPR events in children 8 to less than 18 years old (26), 97 30-second epochs of CCs were analyzed: 74 of 97 (76%) met criteria for CC rate and only 38 of 97 (39%) met criteria for CC depth target compliance.

Several studies have attempted to determine the optimal therapeutic CC depth for pediatric patients. Unlike evidence-based CC depth recommendations for adults, specific evidence for target depth of CC in children is very limited, and thus, CC targets for infants and children have been based on expert

TABLE 4. Event-Level Compliance: Greater Than 60% of Event's Epochs Compliant With American Heart Association Guideline Targets, *n* (%)

Metrics	Total	< 1 yr	1 to < 8 yr	8 to < 18 yr	*p*
Events	112 (100)	38 (34)	42 (38)	32 (29)	
CC fraction	79 (71)	20 (53)	34 (81)	25 (78)	< 0.001
CC rate	53 (47)	12 (32)	21 (50)	20 (63)	< 0.02
CC depth[a,b]	27 (24)	5 (13)	8 (19)	14 (44)	0.004
Absolute[c]		0 (0)	3 (7)		0.3
CC fraction and CC rate	31 (28)	8 (21)	11 (26)	12 (38)	0.3
CC fraction and CC depth[a,b]	15 (13)	3 (8)	6 (14)	6 (19)	0.006
Absolute[c]		0 (0)	2 (5)		0.24
CC rate and CC depth[a,b]	10 (8.9)	2 (5)	2 (5)	6 (19)	0.003
Absolute[c]		0 (0)	1 (2)		1.0
CC fraction, CC rate, and CC depth[a,b]	11 (10)	3 (8)	1 (2)	7 (22)	0.40
Absolute[c]		0 (0)	1 (2)		1.0

CC = chest compression.
[a]Using Guideline ≥ 1/3 Anterior-Posterior chest depth for < 8 yr: ≥ 3.4 cm for < 1 yr and ≥ 4.4 cm for 1 to < 8 yr.
[b]Using ± 10% Guideline absolute depth for 8 to < 18 yr is 4.5–6.6 cm.
[c]Using secondary ± 10% Guideline absolute depth for < 8 yr: 3.6–4.4 cm for < 1 yr and 4.5–5.5 cm for 1 to < 8 yr.
Differences in compliances analyzed using χ^2 analysis.

consensus. Current AHA guidelines and International Liaison Committee on Resuscitation consensus statements recommend a CC depth relative to the APD for children: "…depress the chest at least one third of the anterior-posterior diameter of the chest. This equates to approximately 1.5 inches (4 cm) in infants to 2 inches (5 cm) in children" (8). Hence, the actual depth of compression is determined by the size of the infant or child. These guidelines were developed from information extrapolated from adult CC data, measurements and mathematical modeling of chest CT scans, animal data (17–19), and continued reports of shallow CC delivery by providers.

In a rare, small case series of six cardiac surgery infants (2 wk to 7.3 mo old) requiring CC, a CC depth of half APD produced a higher systolic blood pressure (BP) than CC at one-third APD, yet diastolic pressures were similar at both CC depths (27). However, as coronary perfusion pressure (aortic diastolic BP) is the most reliable method for determining the effectiveness of CPR (28), their investigation reported a CC depth of one-third APD to be preferred over deeper CC depths, thereby reducing potential for internal damage (rib fracture, cardiac contusion). Furthermore, in investigations of chest measurements of pediatric CT scans, one study by Braga et al (18) used the guideline depth of 3.8–5.1 cm (recommended depth at time of study), as the measurement variable. They reported that for the 3 months to 3 years old, a 3.8 cm CC would theoretically be a safe depth, yet compressing 5.1 cm CC would be too deep. In addition, for the 3–8 years old, the (2005) adult recommended range of 3.8–5.1 cm would theoretically be a safe CC depth. Using similar methods, Kao et al (19) measured APD of 36 infants and 38 children and suggested that based on their measurements, that one-third APD of the chest in infants was 3.4 cm and for children 1 to less than 8 years was 4.4 cm. It should be noted, though, that the CT scans used for that study were of chronically ill infants and children, who were likely smaller than the general population.

In our current study, we defined a one-third APD compression target in less than 1 year old as at least 3.4 cm and in 1 to less than 8 years old as at least 4.4 cm depth based on radiologic and anthropometric chest measurement studies (17–19). Consequently, when comparing these data to the ± 10% guideline absolute depth targets for children under 8 years, the target threshold is essentially raised for the two age groups. As such, in the 60-second epoch analysis, CC depth compliance decreased (from 17% to 8%) as well as total compliance (from 5% to 2%) in the less than 1-year events. Likewise, for 1 to less than 8 years events, we found that CC depth compliance and total compliance decreased (from 30% to 17%, and 16% to 11%, respectively). Event-level analysis also demonstrated a decrease for total compliance when using absolute CC depth targets in events of infants less than 1 year, but there was no change in events of children 1 to less than 8 years old.

Comparison to Prior Pediatric Out-of-Hospital Reports

In comparing our current IHCA results with quantitative out-of-hospital cardiac arrest (OHCA) quality metrics captured from 2005 to 2012 by the Resuscitation Outcomes Consortium (20), Emergency Medical Service providers also had difficulty achieving AHA guidelines for CC rate and depth. They analyzed quantitative CC depth for a sample of 153 children less than 18 years

($n = 0$ for age 0 to < 1 yr, $n = 34$ for age 1 to < 12 yr; $n = 119$ for age 12–18 yr) using contemporary compliance criteria (e.g., ≥ 3.8 cm depth prior to 2010, ≥ 5.0 cm after 2010). In OHCA in children 1 to less than 18 years, they report CCF of 0.76 ± 0.17, CC rate of 118.7 ± 22.2 per minute, and CC depth of 3.95 ± 1.07 cm. The proportion of OHCA events meeting AHA compliance targets was low: 53% for CCF, 36% for CC rate, 58% for CC depth, and only 22% of events met criteria for both CCF and CC rate. In arrests from 2011 and later, compliance with current 2015 AHA Guidelines for CC depth (≥ 5.0 cm) was not common (16%), with 0% of events in 1–11 years old and only 12 of events (21.8%) in 12–18 years old meeting AHA targets.

It is generally hypothesized that when real-time automated CPR feedback is given to a CC provider, they will optimize their CC performance in real time. Although audiovisual feedback should promote delivery of CC depths closer to guideline targets, the authors postulate that there are a number of situations in which feedback may be "ignored": 1) For those children under the age of 8 years, the defibrillator provides no corrective voice prompts to indicate that the provider should compress deeper, and thus the provider or CPR coach needs to be able to continually see the visual display of the defibrillator to use it for real-time corrective feedback; 2) Providers were distracted during CC delivery due to competing priorities and commotion during a code; 3) Target compression depth may not be achievable in the younger children; 4) Some providers may have been guided by physiologic data available—arterial catheter, end-tidal CO_2, etc—to titrate their compression depth, superseding CC depth guideline targets; 5) Rescuer fear of doing harm. In a study of adult out-of-hospital CPR by Tomlinson et al (29), they found that even with real-time audiovisual directive and corrective CPR feedback, rescuers often ignore automated feedback prompting deeper compressions when they subjectively feel that they have provided adequate force. Rescuer fear of doing harm to the patient by delivering a CC that may ultimately be harmful is an ongoing issue and barrier to providing adequately deep CCs in all age groups.

In addition to 2015 consensus recommended guidelines for quality of CPR, we characterized a new potential pediatric metric, CCRV, which may serve as a surrogate for chest recoil mechanics and has been suggested in some studies to potentially be associated with survival outcomes in adults (30–33). CCRV may evolve to be a metric related to "full release" and "chest recoil" but has not yet been reported or associated with survival outcomes in children. We found that as age increases, so does CCRV, which requires additional investigation to characterize the physiologic changes in compliance and anatomic changes to the chest over the course of a CPR event.

The 2015 Institute of Medicine (IOM) report on Cardiac Arrest (34) and 2013 AHA consensus on CPR Quality (13) recognized that there is considerable variation in the IHCA treatment and care delivery across hospitals. The IOM recommends that future clinical studies be built upon a foundation of understanding the implementation and effectiveness of existing therapies and guidelines, with generation of data streams to inform evidence-based practices. Specific collaborative quality improvement strategies for cardiac arrest include measuring processes and outcomes associated with resuscitation, benchmarking performance against best practices and data from comparable systems, and providing feedback to providers and teams (35). Most previous quantitative pediatric in-hospital CPR quality data have come from single-center studies and small case series in older children 8 to less than 18 years (6, 7, 10–12, 26, 35, 36), one in younger children under the age of 8 years (9), and none in infants under the age of 1 year.

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 (37–39) and CC depth (7, 21, 40, 41). In one pediatric single-center, before-after interventional study, postcardiac arrest debriefing was used to improve in-hospital CPR quality and AHA guideline compliance (24), and these improvements were associated with a clinically and statistically significant improvement in survival to discharge with good neurologic outcome. As the rate of AHA compliance in that single-center study (CCF 82%, CC rate 90%, absolute CC depth 91%) with an intensive training and debriefing program was much higher than what we report here, interventions to improve in-hospital pediatric CPR quality are potentially feasible. This initial report from the pediRES-Q collaborative is focused on the "process of care" during pediatric IHCA CPR and was not intended and is underpowered to address the interesting and important association of compliance with AHA guidelines with short- or long-term survival outcomes. Thus, we have deferred this critical analysis. The importance of this study is that for the first time, this multicenter pediatric IHCA pediRES-Q quality improvement collaborative describes the landscape of CPR quality for children and provides new benchmark information on the translation and implementation of pediatric guidelines for IHCA.

LIMITATIONS

This study has limitations. First, this study was not powered to address short- or long-term survival association with quality of CPR or compliance with current AHA guideline targets. Our network participants are volunteers interested in the delivery of high-quality CPR, and the cases reported from each facility were based on local resources dedicated to data collection and entry so were not consecutive. Thus, the cases reported were a convenience sample and may not be completely representative of the true quality performance of all IHCAs at these institutions, nor we do not know if these data are generalizable or representative of CPR quality outside of this resuscitation-oriented collaborative network. Also, of those cases reported, the data were only used where CPR quality metrics were able to be collected through electrode pads and where data quality was adequate, which has likely biased the sample toward longer CPR events and older children (7). The authors cannot confirm how long CPR was provided before sensor placement or exact sensor pad placement location in most cases. Thus, to account for potential confounding by anterior apical (instead of usual anterior-posterior) pad placement and mattress compression depth, we excluded epochs of CPR with anterior apical pad placement and with depth reported as less than 1.5 cm or greater than 8 cm, as these depths are likely artefactual based upon improper pad placement. In addition, although the dual sensor electrode pads eliminate "mattress displacement" issues in this current descriptive study, we prospectively selected ± 10% target depth as the minimally clinically important margin for compression depth. Furthermore, ventilation rate and incomplete release between compressions during CPR, which are potentially important quality variables, were not consistently available. In addition, it was beyond the scope of this article to report the issues of provider fatigue, CC variability, and changes in CC performance over time (provider-influenced or patient structurally influenced) yet is of great importance. Finally, the definitions of AHA guideline compliant CPR targets, while based upon the best available science (8, 13) and consistent with previous publications (7, 21, 40), are somewhat arbitrary and based upon expert consensus. We cannot be certain that the current AHA quality targets are the optimal cutoffs for survival. 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 and provides new benchmark information on the translation and implementation of pediatric guidelines for IHCA.

CONCLUSIONS

Across a 12-center international pediatric IHCA resuscitation collaborative, we characterized the quality of pediatric in-hospital CC quality metrics and found that CCs often do not meet 2015 AHA guideline CCF, CC rate and CC depth targets. Compliance is poor for both infants and children, with the most difficulty in achieving compliance with current guideline CC depth in younger children.

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