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American Heart Association Cardiopulmonary Resuscitation Quality Targets are Associated with Improved Arterial Blood Pressure During Pediatric Cardiac Arrest

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Abstract

Aim—To evaluate the association between cardiopulmonary resuscitation (CPR) quality and hemodynamic measurements during in-hospital pediatric cardiac arrest. We hypothesized that AHA recommended CPR rate and depth targets would be associated with systolic blood pressures 80 mmHg and diastolic blood pressures 30 mmHg.

Methods—In children and adolescents < 18 years of age who suffered a cardiac arrest with an invasive arterial catheter in place, a CPR monitoring defibrillator collected CPR data which was synchronized to arterial blood pressure (BP) tracings. Chest compression (CC) depths were corrected for mattress deflection. Generalized least squares regression estimated the association between BP and CPR quality, treated as continuous variables. Mixed-effects logistic regression estimated the association between systolic BP 80 mmHg/diastolic BP 30 mmHg and the AHA targets of depth 38 mm and/or rate 100/min.

Results—Nine arrests resulted in 4,156 CCs. The median mattress corrected depth was 32 mm (IQR 28 – 38); median rate was 111 CC/min (IQR 103 – 120). AHA depth was achieved in 1090/4156 (26.2%) CCs; rate in 3441 (83.7%). Systolic BP 80 mmHg was attained in 2516/4156 (60.5%) compressions; diastolic 30 mmHg in 2561/4156 (61.6%). A rate 100/min

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was associated with systolic BP ≥ 80 mmHg (OR 1.32; CI⁹⁵ 1.04, 1.66; $p=0.02$) and diastolic BP ≥ 30 mmHg (OR 2.15; CI⁹⁵ 1.65, 2.80; $p<0.001$). Exceeding both (rate ≥ 100 /min and depth ≥ 38 mm) was associated with systolic BP ≥ 80 mmHg (OR 2.02; CI⁹⁵ 1.45, 2.82; $p<0.001$) and diastolic BP ≥ 30 mmHg (OR 1.48; CI⁹⁵ 1.01, 2.15; $p=0.042$).

Conclusions—AHA quality targets (rate ≥ 100 /min and depth ≥ 38 mm) were associated with systolic BPs ≥ 80 mmHg and diastolic BPs ≥ 30 mmHg during CPR in children.

Keywords

blood pressure; cardiac arrest; cardiopulmonary resuscitation; chest compression; pediatric; quality

Introduction

Cardiopulmonary resuscitation (CPR) quality has been highlighted as an important determinant of survival outcome after cardiac arrest. Specific quality targets such as achieving adequate chest compression depths^{1,2} and rates³, and limiting interruptions in CPR^{1,4–7} have all been associated with improved survival outcomes after adult cardiac arrest. However, these same quality targets in infants and children have largely been developed by expert clinical consensus, using data extrapolated from animal, manikin, mathematical modeling, and adult studies, with little data collected from actual children. This paucity of child-specific data highlights an important gap in the pediatric resuscitation knowledge base.

Therefore, the objective of this study was, for the first time, to associate specific quantitative CPR quality targets (chest compression depth, rate, and incomplete release) to hemodynamic measurements prospectively obtained during actual in-hospital pediatric cardiac arrest resuscitation. We hypothesized that 2005 AHA recommended quality targets (rate ≥ 100 /min; depth ≥ 38 mm) would be associated with systolic blood pressures ≥ 80 mmHg and diastolic blood pressures ≥ 30 mmHg.

Methods

Protocol/Consent

This investigation was a prospective observational study with the primary objective to quantitatively associate CPR quality with invasively measured arterial blood pressure. Data were collected under study protocols approved by the Institutional Review Board at The Children's Hospital of Philadelphia. Data collection procedures were completed in compliance with the guidelines of the Health Insurance Portability and Accountability Act (HIPAA) to ensure subject confidentiality. Written consent was obtained from all health care providers who participated in the resuscitation attempts and from the parents of pediatric cardiac arrest victims < 8 years of age who had the modified CPR recording sensor (described below) deployed during their resuscitation. For those arrest subjects ≥ 8 years of age, a waiver of consent was obtained from the IRB.

CPR Recording Defibrillator

The Heartstart MRx defibrillator with Quality-CPR (Q-CPR) Technology utilized in this investigation was jointly designed by Philips Healthcare (Andover, MA USA) and Laerdal Medical AS (Stavanger, Norway) and is currently marketed in the United States for use in children ≥ 8 years of age. Each defibrillator has an oval compression sensor or “puck” that is placed on the lower part of the sternum between the rescuer's hand and the victim's chest. The Q-CPR sensor records accelerometer and force signals and transmits this data to the

MRx defibrillator for storage, and for later analysis of chest compression (CC) data (e.g., rate, depth, residual leaning force). The defibrillator monitor also provides real-time audiovisual feedback when CPR does not comply with American Heart Association (AHA) quality recommendations. At the time of this study, feedback was supplied in accordance with 2005 AHA Guidelines⁸ (depth 38 mm (1.5 inches), rate 90 CC/min or 120 CC/min, pauses of 15 seconds, and measurable residual leaning force 2500 grams). In order to collect data on younger children (i.e., less than 8 years of age), a modification was made to the Q-CPR Sensor to accommodate the smaller sternum of younger subjects, the automated feedback was silenced (no quantitative absolute depth recommendations were available from the AHA in 2005), and written *prospective* consent was obtained from these subjects prior to their arrest event (i.e., potential subjects were pre-identified). Importantly, the software/algorithms for determining CPR quality parameters were unchanged in the modified compression sensor.

Subject Enrollment

Consecutive cardiac arrests requiring at least one minute of CCs with Q-CPR technology deployed in patients < 18 years of age occurring in the pediatric intensive care unit (PICU) of a children's hospital were screened for inclusion in the study. Cardiac intensive care unit (CICU) patients were not included because the Q-CPR defibrillator is not deployed during resuscitation there. All subjects had invasive arterial catheters in place at the time of enrollment. Time during the compression delivery when Q-CPR technology was not utilized (e.g., prior to sensor deployment at the onset of compressions (~ 1 – 2 minutes on average)) or when arterial pressure tracings were not available (e.g., during blood gas collection) was excluded from analysis.

Study Variables

The primary outcome variables of this study were systolic and diastolic arterial blood pressure (BP) recorded from an invasive arterial catheter in place at the time of cardiac arrest. The prospectively designated target arterial BPs for analysis were systolic 80 mmHg and diastolic 30 mmHg. These thresholds were chosen not only based upon age-related norms⁹, but specifically for diastolic pressure, because of the consistent relationship of this threshold (diastolic BP 30 mmHg) with improved short term survival in animal^{10–12} and adult investigations.¹³ Arterial waveforms were printed from the PICU central monitoring system (GE Medical Systems, Inc.) and subsequently digitized using a graphics program (DigitizeIt; Version 1.5.8). This process allowed extraction of de-identified numerical X (time in seconds) and Y (arterial BP) data that was then time synchronized to the specific CC generating each pressure measured from the arterial catheter. Systolic BP was sampled at the peak of the arterial pressure tracing; diastolic BP was sampled during mid-diastole. The predictor CPR quality variables were CC depth in millimeters (corrected for mattress deflection (see below)^{14,15} and instantaneous compression rate (calculated as 60 divided by the time between adjacent chest compressions). Incomplete chest wall recoil (leaning between compressions) was accounted for in the analysis by subtracting the leaning depth (mm) from the maximum compression depth attained, with the final predictor variable equaling the effective “stroke depth” of compression. Any calculated rates less than 30 per minute were assumed to have come from nonadjacent compressions (i.e., the first compression in a series) and were excluded from the analysis. These predictor variables were also analyzed in dichotomous form. As defined by 2005 guidelines⁸, AHA recommended quality CPR was defined as rate 100 CC/min and depth 38 mm. To standardize the time during the events from which data was sampled, only the first 1000 delivered compressions were included in the final analysis.

The MRx uses the accelerometer and force signals to calculate the movement of the Q-CPR sensor. For a patient laying on a hard surface, the sensor movement equals the CC depth. However for compressions on a patient in a bed, this total movement is comprised of the actual compression of the patient's chest as well as compression of the mattress. The mattress compression portion is undesired in the compression depth signal and was removed using a previously reported analytical process.¹⁵ The mattress depth portion was removed from the MRx depth signal, and reported as "correctedCC depth". Quality data (maximum and leaning depths, rate, and peak force) were identified for each compression and outputted for statistical analysis. The MRx depth signal processing and subsequent quantification of quality data was done using MATLAB (Mathworks, Natick, MA).

Statistical Analysis

Resuscitation events that required CC delivery due to sudden cardiac arrest (loss of cardiac mechanical activity documented by loss of pulse and respiratory effort), acute respiratory compromise leading to cardiac arrest, and bradycardia with inadequate perfusion were considered together in the analysis. Standard descriptive summaries (medians and percentiles) were calculated for CPR quality and arterial blood pressure data for each event. Generalized least squares regression was used to estimate associations between CC rate and depth, treated as continuous variables, and arterial blood pressure. Events were assumed to be independent with unequal variance. An event-specific auto-regressive (AR1) correlation structure was used to account for temporal correlation within events. Logistic regression was used to evaluate the association between BP thresholds (SBP $\geq$ 80 mmHg, DBP $\geq$ 30 mmHg) and AHA recommended CPR quality targets (rate $\geq$ 100/min, depth $\geq$ 38 mm). Distinct independent models were constructed for both outcome variables: systolic BP $\geq$ 80 mmHg; and diastolic BP $\geq$ 30 mmHg. Event-specific fixed effects were used to account for within-event correlation. P values less than 0.05 were considered statistically significant. Statistical analysis was completed using Stata (Version 12.0, StataCorp, College Station, TX) and R (Version 2.14, R Development Core Team, Vienna, Austria).

Results

During the time period between October 2006 and September 2011, 4,156 evaluable CCs were collected from 9 *consecutive* pediatric patients < 18 years of age who suffered a cardiac arrest in the PICU of at least one minute duration with an invasive arterial line in place at the time of the arrest.

Patient demographic and cardiac arrest data are presented in Table 1. Median age was 14 years (range: 1.75 – 17). Median weight was 48 kilograms (range: 11.7 – 55). Slightly more arrests were in male subjects: 5 of 9 (56%); and more occurred during daytime hours: 5 of 9 (56%). First documented event rhythm was bradycardia in 4 patients (44%), pulseless electrical activity/asystole in 1 (11%), and pulseless ventricular tachycardia/ventricular fibrillation in 4 (44%). Return of spontaneous circulation was achieved in 2 of 9 (22%) events.

The overall median mattress corrected CC depth delivered was 32 mm (IQR 28 – 38); median rate was 111 CC/min (IQR 103 – 120); median applied maximum force was 32 kilograms (IQR 27 – 39); and the median leaning force was 1.7 kilograms (IQR 1.2 – 2.3). For reference and comparison to previous reports on in-hospital CPR quality^{1,16–18}, the median uncorrected CC depth in this study was 49 mm (IQR 43 – 56), well above the 2005 AHA recommended depth. The median systolic blood pressure achieved during compressions was 87 mmHg (IQR 72 – 139); the median diastolic pressure was 32 mmHg (IQR 27 – 44). AHA compliant corrected depth ($\geq$ 38 mm) was achieved in 1090/4156 (26.2%) compressions; AHA compliant rate in 3441 (83.7%). Systolic BP threshold $\geq$ 80

mmHg was attained in 2516/4156 (60.5%) compressions; diastolic threshold ≥ 30 mmHg in 2561/4156 (61.6%).

Association of CPR Quality and Arterial Blood Pressure

Table 2 presents descriptive summaries calculated at the event level for CPR quality and arterial BP variables. Table 3 presents univariable associations between individual CPR quality variables and arterial BP. In these univariable analyses, while all but one association met statistical significance, systolic BP had the most clinically relevant association with improved CC rate, depth and force. Associations with diastolic BP were less clinically robust (point estimates between -0.6 and 0.6 mmHg). In an exploratory analysis, these associations were robust across subjects with and without native cardiac ejection (i.e., bradycardia with poor perfusion vs. other initial cardiac rhythms). In particular, when the pulseless arrest group was analyzed separately from the patients with bradycardia/poor perfusion, the statistically significant relationship between CC depth/force and SBP remained ($p < 0.01$).

Table 4 presents odds ratios evaluating the association of AHA recommended CPR quality targets (rate ≥ 100 CC/min and/or depth ≥ 38 mm) with arterial pressure targets (systolic ≥ 80 mmHg; diastolic ≥ 30 mmHg). The top two rows evaluate the association between having one CPR quality variable within AHA targets (either rate OR depth) compared to poor CPR quality (i.e., $\text{depth} < 38 \text{ mm}$ AND $\text{rate} < 100/\text{min}$). In this analysis, exceeding the AHA rate target ($\geq 100/\text{min}$) was associated with both systolic BP ≥ 80 mmHg (OR 1.32; CI⁹⁵ 1.04, 1.66; $p=0.02$) and diastolic BP ≥ 30 mmHg (OR 2.15; CI⁹⁵ 1.65, 2.80; $p<0.001$) (top row). However, exceeding the AHA depth target alone (≥ 38 mm) was not associated with attaining either BP threshold compared to poor CPR quality (middle row). Importantly, exceeding both AHA recommended targets (rate $\geq 100/\text{min}$ and depth ≥ 38 mm) was associated both with systolic BP ≥ 80 mmHg (OR 2.02; CI⁹⁵ 1.45, 2.82; $p<0.001$) and diastolic BP ≥ 30 mmHg (OR 1.48; CI⁹⁵ 1.01, 2.15; $p=0.042$) (bottom row).

Discussion

This study establishes that during real in-hospital pediatric cardiac arrest resuscitation, 2005 AHA recommended CPR quality targets of CC (rate $\geq 100/\text{min}$ and/or depth ≥ 38 mm) are associated with systolic blood pressures ≥ 80 mmHg and diastolic blood pressures ≥ 30 mmHg. Clinically, depth was most associated with systolic pressure: for every 10 mm increase in CC depth, average systolic BP improved >15 mmHg (Table 3). Further, CPR with both rate *and* depth within AHA quality targets was significantly associated with diastolic BPs ≥ 30 mmHg, a threshold associated with short-term survival in both animals and adults.^{10–13}

Performing AHA recommended compression rates, even when depth was not in target range, was associated with a higher odds of achieving arterial blood pressure targets in this investigation; however, the reverse was not true. This should not lead the reader to conclude that rate is more important than depth. The ranges of depth and rates in this investigation were narrow (small variance in care due to daily CPR trainings^{19–21} and automated feedback^{22–24}), and poor CPR quality was uncommon. Even though achieved corrected compression depths were between 30–40 mm in most cases, note that these depths are corrected for leaning and mattress deflection (a penalty of ~ 15 mm on average¹⁴). In this investigation, by removing these artifacts, we have reported actual displacement of the sternum towards the spine. As a result, the depths performed in this investigation would be in the range of 45 to 55 mm when mattress effect is not accounted for in the determination, as in nearly all previous publications of CPR quality.^{1,16–18} Therefore, finding statistical associations with pressure over a narrow range of quality (our predictor variables) becomes

difficult. In the end, the results do not necessarily imply that compression rate is more important than depth; rather, the data support the conclusion that performing high quality CPR is associated with improved arterial blood pressure.

Irrespective of arrest etiology, generation of vital organ blood flow by CPR is related to survival outcome.^{10,13} During CPR, blood flow and survival are both directly related to coronary perfusion pressure (CPP).^{11,13,25} As CPP is mathematically the difference between aortic diastolic BP and the right atrial diastolic pressure, improving diastolic pressure improves CPP.²⁶ During adult resuscitation, achieving a diastolic blood pressure of 30 mmHg improves resuscitation outcome.¹³ Therefore, in this investigation, we have associated CPR quality with a clinically relevant surrogate outcome.

An important investigation that must be mentioned when discussing pediatric CPR quality and arterial blood pressure is the 2010 case series by Maher et al. published in *Resuscitation*.²⁷ In this study of infants post-cardiac surgery, invasive arterial BP was associated with qualitative CC depths (i.e., depths estimated by crude visual observation, without quantitative measurement). Although this was a small series with only qualitatively estimated CC depths, this was the first study to collect actual data from children supporting CPR guidelines. This study provided evidence that deeper compressions (1/2 Anterior-Posterior (AP) depth) improved arterial BP. However, this study was limited in using qualitatively estimated compression depths, rather than accurate quantitative measurements as utilized in this investigation. In fact, other studies, two radiographic^{28,29} and one using external anthropometric measurements³⁰, have challenged the notion that 1/2 AP depth is even attainable in most children. Similar to the Maher study, our data suggests that deeper compressions improve arterial blood pressure, however, our investigation was completed when 2005 CPR guidelines were in effect, and we have very few compressions that exceed 50 mm, the threshold set with the new 2010 guidelines³¹, particularly when corrected for mattress deflection. Therefore, we are unable to comment on whether providing *even deeper* compressions would further improve blood pressure. However, our results are consistent with the findings of Stiell et al., who associated achieving 2005 depth targets (>38mm) with improved survival after adult out-of-hospital cardiac arrest.²

This study has several limitations. First, this was a small study of primarily post-pubertal subjects. Whether or not these findings can be generalized to all pediatric subjects is an important concern. Second, we used a clinically meaningful surrogate outcome (BP); however, the relationship between these surrogates of outcome (SBP >80 mmHg and DBP >30 mmHg) and survival remains an unanswered question. Third, while we considered several CPR quality targets in our investigation, two other important markers of quality (no flow fraction: the percentage of time during cardiac arrest when CPR is not performed^{4,6,7}; and ventilations^{32,33}) were not considered in the analysis due to power concerns. In the future, a multi-variable predictor of good CPR quality which incorporates all of these parameters should be investigated. Fourth, surprisingly there was no significant association between CPR quality and diastolic pressure; however, this negative finding may be explained by the numerous investigations that have associated diastolic pressure more with vasopressor administration, rather than CC quality *per se*.^{34–37} Additionally, in regards to vasopressor dosing, while this study is unable to definitively answer the question as to which is a more important determinant of pediatric diastolic pressure during CPR, (vasopressor dosing vs. CC quality), all but one subject received standard AHA recommended pediatric advanced life support dosing of epinephrine (10 mcg/kg every 3 to 5 minutes), thereby limiting the variation of this important variable across our subjects. Finally, while this study provides important information regarding the association of compression quality with hemodynamic measurements, the question as to what “monitor” rescuers use to actually

guide their compression quality (i.e., invasive blood pressure, end tidal carbon dioxide, or more qualitative measures) remains unanswered.

Conclusions

During actual resuscitation of children and adolescents, CPR rate and depth were significantly associated with hemodynamic outcome. AHA recommended quality targets (rate 100/min and/or depth 38 mm) were associated with systolic blood pressures 80 mmHg and diastolic blood pressures 30 mmHg during CPR, values previously associated with survival outcomes in animals and adult humans. Future studies are needed to evaluate the association between CPR quality, arterial blood pressure and pediatric long-term neurological survival.

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Abbreviations

AHA	American Heart Association
BP	Blood Pressure
CC	chest compression
CPR	cardiopulmonary resuscitation

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Table 1

Patient demographic and cardiac arrest event data.

Subject Demographic Data (n=9)	
Age: years median (range)	14 (1.75 – 17)
Weight: kilograms median (range)	48 (11.7 – 55)
Sex: male n (%)	5 (56)
Descriptive Data of Arrests *	
Time of Arrest	
Day/Evening (7AM – 10:59PM)	5 (56)
Night/Weekends [†] (11PM – 6:59AM)	4 (44)
Initial Rhythm	
Bradycardia	4 (44)
Asystole/PEA	1 (11)
Ventricular Fibrillation Pulseless Ventricular Tachycardia	4 (44)
Return of Spontaneous Circulation	2 (22)

* Data presented as n (%).

[†]Weekends indicates time between Friday 11PM and Monday 6:59AM.

Table 2

Summary statistics for CPR quality and arterial blood pressure for each event.

Subject	Age (yrs)	Depth (mm)	Rate (CC/min)	Force (kg)	NFF (%)	SBP (mmHg)	DBP (mmHg)	MAP (mmHg)
1	16	47 (42, 51)	125 (118, 133)	30 (26, 34)	17	38 (34, 44)	18 (17, 20)	25 (23, 27)
2	13	36 (32, 39)	113 (107, 120)	33 (28, 38)	14	82 (74, 95)	34 (31, 37)	50 (45, 56)
3	14	29 (26, 30)	113 (109, 118)	23 (21, 26)	7	82 (78, 87)	32 (30, 34)	49 (47, 51)
4	14	40 (38, 41)	111 (105, 118)	31 (29, 36)	30	65 (58, 73)	29 (27, 32)	41 (38, 45)
5	17	20 (18, 23)	109 (100, 122)	36 (29, 38)	11	93 (84, 104)	28 (24, 33)	50 (45, 57)
6	15.5	31 (29, 33)	103 (97, 109)	29 (27, 32)	15	75 (58, 91)	28 (26, 31)	44 (37, 50)
7	17	44 (39, 49)	107 (100, 113)	50 (43, 56)	15	93 (76, 123)	22 (19, 25)	45 (38, 57)
8	1.75	30 (27, 33)	104 (100, 109)	25 (20, 28)	4	80 (75, 85)	37 (36, 40)	52 (50, 54)
9	6.4	28 (26, 30)	115 (109, 122)	33 (29, 44)	1	181 (166, 204)	62 (59, 64)	101 (95, 111)

Data presented as median (IQR).

SBP indicates systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure; NFF, no-flow fraction (percentage of time during cardiac arrest without provision of CPR).

Table 3

Univariable associations between individual CPR quality variables and arterial blood pressure.

	Depth (10mm)	Rate (20 CC/min)	Force (10Kg)
SBP	15.5 (14.1, 17.0) *	2.6 (1.8, 3.5) *	14.3 (13.5, 15.2) *
MBP	4.8 (4.2, 5.4) *	0.9 (0.5, 1.2) *	5.2 (4.8, 5.6) *
DBP	-0.6 (-0.9, -0.2) †	-0.02 (-0.2, 0.2)	0.6 (0.4, 0.8) *

Data presented as point estimate (CI⁹⁵); point estimates correspond to the difference in mean pressure (mmHg) according to noted increases in depth (10 mm), rate (20 CC/min), and force (10 Kg).

SBP indicates systolic blood pressure; MBP, mean blood pressure; and DBP, diastolic blood pressure.

* p<0.001;

† p=0.002.

Table 4

Relative odds of attaining threshold values of systolic blood pressure (≥ 80 mmHg) and diastolic blood pressure (≥ 30 mmHg) according to CPR quality thresholds.

	SBP ≥ 80	DBP ≥ 30
Rate Only ≥ 100 CC/min	1.32 (1.04, 1.66) *	2.15 (1.65, 2.80) †
Depth Only ≥ 38 mm	1.04 (0.63, 1.71)	0.97 (0.52, 1.79)
Rate and Depth	2.02 (1.45, 2.82) †	1.48 (1.01, 2.15) //

Data presented as odds ratios (CI⁹⁵); all odds ratios relative to poor CRP quality (rate < 100 CC/min and depth < 38 mm).

SBP indicates systolic blood pressure; DBP, diastolic blood pressure.

*
p=0.02;

†
p<0.001;

//
p=0.042.