Available online at www.sciencedirect.com

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Clinical paper

Hemodynamic effects of chest compression interruptions during pediatric in-hospital cardiopulmonary resuscitation

Ryan W. Morgan *, *William P. Landis*, *Alexandra Marquez*, *Kathryn Graham*, *Anna L. Roberts*, *Kasper G. Lauridsen*, *Heather A. Wolfe*, *Vinay M. Nadkarni*, *Alexis A. Topjian*, *Robert A. Berg*, *Todd J. Kilbaugh*, *Robert M. Sutton*

The Children's Hospital of Philadelphia, Department of Anesthesiology and Critical Care Medicine, 3401 Civic Center Blvd, Philadelphia, PA 19104, United States

Abstract

Aim: Animal studies have established deleterious hemodynamic effects of interrupting chest compressions. The objective of this study was to evaluate the effect of interruptions on invasively measured blood pressures (BPs) during pediatric in-hospital cardiac arrest (IHCA).

Methods: This was a single-center, observational study of pediatric (<18 years) intensive care unit IHCAs in patients with invasive arterial catheters in place. Interruptions were defined as ≥1 s between chest compressions. Diastolic BP (DBP) and systolic BP (SBP) were determined for individual compressions. For the primary analysis, the average DBP and SBP of the 20 compressions preceding each interruption were compared to the average DBP and SBP of the first 20 compressions following each interruption utilizing non-parametric paired analyses. Linear regression evaluated the change in DBP during interruptions and following interruptions.

Results: Thirty-two IHCA events met inclusion criteria, yielding 161 evaluable interruptions. The median age was 2.1 years. Return of circulation was achieved in 24 (75%). The median interruption duration was 2.4 [1.4, 7.0] seconds. Most patients were intubated pre-arrest and received epinephrine during CPR. BPs were not different pre- vs. post-interruption (DBP: 28.7 [21.6, 38.2] vs. 28.3 [21.0, 37.4] mmHg, $p = 0.81$; SBP: 82.0 [51.7, 116.7] vs. 85.4 [55.7, 122.2] mmHg, $p = 0.07$). DBP decreased 8.41 ± 0.73 mmHg ($p < 0.001$) during the first second of interruptions and 0.19 ± 0.02 mmHg/s ($p < 0.001$) in subsequent seconds.

Conclusions: BPs following chest compression interruptions did not differ from pre-interruption BPs. These findings suggest that in the setting of high-quality in-hospital CPR, brief chest compression interruptions do not have persistent detrimental hemodynamic impact.

Keywords: Cardiac arrest, Cardiopulmonary resuscitation, Hemodynamics, Pediatrics

Introduction

More than 6000 children suffer in-hospital cardiac arrests (IHCAs) annually in the United States,[1] and less than half survive to hospital discharge.[2,3] In recent years, considerable effort has been directed toward improving cardiopulmonary resuscitation (CPR) quality as a means to increase survival rates. Among these quality targets is the maximization of the chest compression fraction (CCF), the percentage of time during a CPR event spent delivering chest compressions. Interruptions in chest compressions, especially when prolonged or frequent, are associated with worse survival rates in adult cardiac arrest.[4–7]

One mechanism by which chest compression interruptions result in lower rates of survival is through deleterious effects on systemic and coronary hemodynamics. In both experimental and clinical pediatric

* Corresponding author at: Children's Hospital of Philadelphia, 3401 Civic Center Boulevard, 6 Wood– 6011, Philadelphia, PA 19104, United States.
E-mail address: morganr1@email.chop.edu (R.W. Morgan).

https://doi.org/10.1016/j.resuscitation.2019.03.032
Received 12 February 2019; Received in revised form 12 March 2019; Accepted 20 March 2019

CPR, invasively measured hemodynamics, specifically diastolic blood pressure (DBP) and coronary perfusion pressure (CoPP), are associated with survival.[8–10] Expert consensus statements and guidelines advocate for monitoring these hemodynamic parameters and titrating therapies to optimize them.[11,12] Pre-clinical data demonstrate a significant and sustained decline in CoPP during regular interruptions in chest compressions for the delivery of rescue breaths that persists upon restarting chest compressions. However, these studies utilized models of bystander CPR for out-of-hospital cardiac arrest with prolonged interruption durations that are unlikely to be entirely extrapolatable to the inpatient setting.[13,14] The hemodynamic effects of interruptions in the setting of high-quality CPR during pediatric IHCA have not been described. Thus, the primary objective of this study was to compare invasively measured hemodynamics before and after an interruption in chest compressions in children with IHCA. We hypothesized that post-interruption BPs would be significantly lower than pre-interruption BPs.

Methods

This was an observational cohort study among prospectively enrolled, consecutive, hospitalized patients >37 weeks' corrected gestational age and <18 years of age who received at least one minute of CPR for IHCA between June 1, 2013 and November 30, 2018 in the pediatric intensive care unit (PICU) of a quaternary care center. The study was approved with waiver of informed consent by the Institutional Review Board at the Children's Hospital of Philadelphia.

To be eligible for the study, patients were required to have arterial BP monitoring at the onset of CPR and for at least one minute during CPR. Cardiac arrests were identified through a 24-h paging system and an intense daily research coordinator screening procedure. A research coordinator or study investigator then either printed or digitally captured bedside monitor waveform data (BedmasterEX; Excel Medical, Jupiter, FL). Only the first ten minutes of waveform data were collected for each patient. Arterial BP, electrocardiogram, respiratory plethysmography, central venous pressure, and pulse oximetry waveforms were evaluated to determine stops and starts in CPR. If waveform quality did not permit an accurate determination of the start or stop in CPR or if there was underlying spontaneous circulation (systolic BP [SBP] ≥40 mmHg for infants <1 year of age or ≥50 mmHg for older children, and a pulse pressure of ≥10 mmHg) during the interruption, that interruption was excluded. Events were excluded if there was not at least one evaluable interruption in chest compressions of at least one second in duration. In addition to bedside monitor waveform data, research coordinators prospectively collected patient demographics and standardized Utstein-style cardiac arrest and CPR data.[15] Return of circulation (ROC) was the primary event outcome, defined in concordance with Utstein guidelines as sustained return of spontaneous circulation (ROSC) ≥20 min or ROC via extracorporeal membrane oxygenation.[15]

Waveform analysis

For CPR events meeting inclusion criteria, waveforms were either printed from a central monitoring system and manually digitized or electronically acquired in digital format. They were de-identified and analyzed by a trained research coordinator and an investigator blinded to other clinical data. Using Plot Digitizer (open source software; https://sourceforge.net/projects/plotdigitizer), SBP was sampled at the peak of the arterial pressure tracing for each compression and DBP was sampled during mid-diastole for each compression. This process included determination of the time (in seconds from the start of CPR) of each SBP and DBP data point. Periods of chest compression interruptions and intermittent spontaneous circulation were identified using the arterial BP waveform and the overall complement of waveform data (e.g., respiratory plethysmography, central venous pressure). An interruption was defined as any lapse of ≥1 second between SBP peaks if there was not underlying ROSC. This short duration was chosen for the following reasons: (1) actual chest compression rates <60 compressions per minute (correlating to >1 second between compressions) are seldom observed in pediatric IHCA[16,17]; (2) substantial decrements in hemodynamics have been observed during the first second of interruptions in animal studies[14]; (3) to be consistent with ongoing multicenter pediatric IHCA work[18]; and (4) to be more inclusive of the typically brief chest compression interruptions in our PICU. The DBP and SBP of the 20 compressions pre- and post-interruption were recorded for analysis, as was the DBP throughout the course of the interruption (Fig. 1). Chest compression fraction was calculated for each event by subtracting the cumulative amount of interruption time from the total duration of the event and dividing by the total duration of the event (excluding periods of unanalyzable waveform data or periods of intermittent spontaneous circulation from both the numerator and denominator).

Statistical analysis

Patient and event characteristics were described as frequencies and percentages or medians and interquartile ranges (IQRs). The pre-interruption baseline was defined as the mean DBP and SBP of the 20 chest compressions immediately preceding each interruption. This number of compressions was chosen after a review of preliminary data to best represent a true baseline while avoiding overlap with earlier interruptions. The following analyses were performed:

1 The primary analysis was a comparison of baseline mean DBP and SBP to the mean DBP and SBP of the 20 chest compressions following the interruption. This number of post-interruption compressions was chosen a priori to represent a clinically meaningful duration of interruption-related hemodynamic effect. The Wilcoxon sign-rank test was utilized with a p-value of <0.05 considered statistically significant.
2 Given previous laboratory data demonstrating a recovery in BPs over a period of several compressions post-interruption,[14] secondary analyses compared the pre-interruption baseline to the mean DBP and SBP of three different compression intervals: early (compressions 1–3), midway (9–11), and late (18–20) in the course of the 20 post-interruption compressions. Wilcoxon signed-rank tests were performed and the Bonferroni correction was utilized to account for repeated measures; p-values of <0.0167 were considered statistically significant.
3 To assess for the effect of patient and cardiac arrest event characteristics on interruption-related hemodynamic changes, we evaluated the association between pre-interruption BP among subgroups according to age category (<1 year, ≥1 year),[19] initial cardiac arrest rhythm (pulseless electrical activity [PEA] or asystole; bradycardia with poor perfusion; and ventricular fibrillation [VF] or pulseless ventricular tachycardia [pVT]),[20] duration of interruption [<5 s, ≥5 s], timing of interruption (minutes

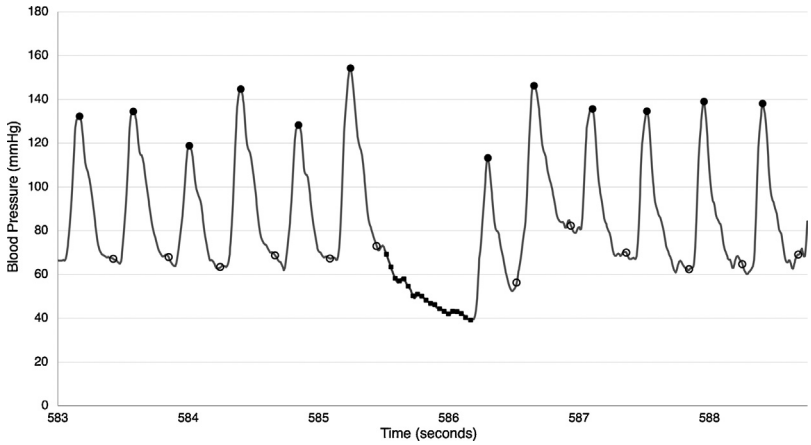

Fig. 1 – Representative peri-interruption hemodynamic sampling.
Invasive arterial waveform demonstrating sampling of waveform peaks for systolic blood pressure values (solid black circles), midway between peaks for diastolic blood pressure values (open circles), and throughout the interruption (black squares).

0–5 of CPR, minutes 5–10 of CPR), and immediate arrest outcome (ROC, death) using Wilcoxon sign-rank tests.

4 To assess the time course of interruption-associated hemodynamic changes, linear regression determined the change in DBP during the interruption with DBP as the dependent variable and time as the independent variable. This was performed both for the first second of each interruption, during which most of the decrement occurred, and for the subsequent duration of the interruption.

5 Changes in DBP and SBP over the course of the 20 post-interruption compressions were determined by linear regression utilizing DBP and SBP as the dependent variables and sequential compression number as the independent variable.

Both regression models accounted for clustering of data points within interruption events.

Results

Over the 66-month study period, 234 PICU cardiac arrest events were identified and evaluated. Of those, 36 events met all inclusion criteria and 32 of 36 had at least one evaluable interruption in chest compressions (Fig. 2). These 32 events occurred among 28 unique patients, with four patients having two events within the same hospitalization. Among the 32 cardiac arrests, there were 161 evaluable interruptions included in the final analyses.

Pre-arrest patient characteristics of the overall cohort are summarized in Table 1. The median age was 2.1 years. The majority of patients had normal or mildly abnormal baseline Pediatric Cerebral Performance Category (PCPC) scoring[21] (PCPC 1–2). Respiratory insufficiency and hypotension or shock were present in the majority of patients.

Cardiac arrest characteristics are summarized in Table 2. Hypotension was the most common immediate cause of cardiac arrest and asystole / PEA was the most common initial cardiac arrest

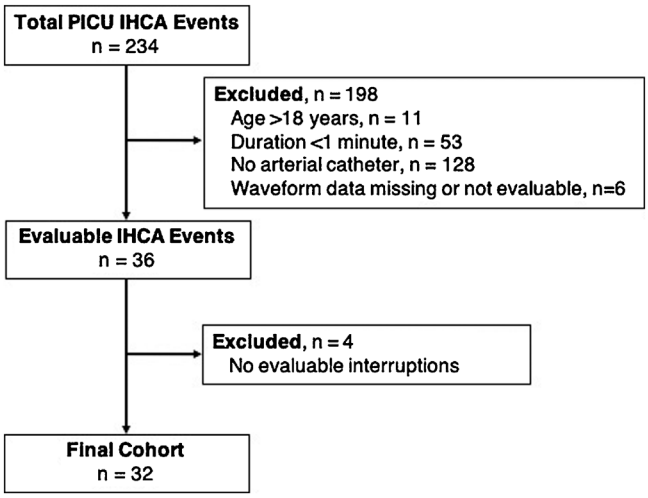

Fig. 2 – Consort diagram.

Table 1 – Patient characteristics.

Patient characteristics (n = 28)	
Age at index arrest (years), median [IQR]	2.1 [0.8, 10.0]
Age categories	
<1 year	10 (35.7%)
≥1 year	18 (54.3%)
Baseline PCPC	
Normal (1)	14 (50.0%)
Mild disability (2)	9 (32.1%)
Moderate disability (3)	1 (3.6%)
Severe disability (4)	4 (14.3%)
Coma/vegetative state (5)	0 (0%)
Pre-existing conditions, n (%)	
Hypotension/shock	19 (67.9%)
Respiratory insufficiency	25 (89.3%)
Congestive heart failure	7 (25.0%)
Pneumonia	7 (25.0%)
Sepsis	9 (32.1%)
Renal insufficiency	9 (32.1%)
Malignancy	0 (0%)
Congenital heart disease	4 (14.3%)
Hospital discharge outcomes (n = 28 index events), n (%)	
Survival	9 (32.1%)
Survival with favorable neurologic outcome[a]	7 (25.0%)
Discharge PCPC (n = 9 survivors)	
Normal (1)	2 (22.2%)
Mild disability (2)	3 (33.3%)
Moderate disability (3)	3 (33.3%)
Severe disability (4)	1 (11.1%)
Coma / vegetative state (5)	0 (0%)

PCPC indicates Pediatric Cerebral Performance Category.
[a] Survival with favorable neurologic outcome defined as PCPC 1–2 or no worse than baseline.

rhythm category. The median duration of CPR was 7.3 min and the median chest compression fraction was 0.95. The median number of evaluable interruptions per event was 5, with a median duration of 2.4 s. The majority of interruptions were <5 s in duration.

There were no differences in DBP or SBP between the 20 compressions prior to each interruption and the 20 compressions following each interruption (Table 3; Fig. 3). There were no hemodynamic differences between pre-interruption values and early, intermediate, or late post-interruption values (Table 3). In subgroup analyses, there were no differences in the hemodynamic changes among age categories, initial cardiac arrest rhythms, interruption durations, interruption timing, or arrest outcomes (Supplemental Table 1).

During interruptions, there was a significant decrement in DBP over the course of the first second (-8.41 ± 0.73 mmHg/s, $p < 0.001$). The decrement in DBP continued to a lesser degree in subsequent seconds (-0.19 ± 0.02 mmHg/s, $p < 0.001$). Following the interruption, there was a significant increase in DBP ($+0.13 \pm 0.06$ mmHg/compression; $p = 0.03$) and SBP ($+0.42 \pm 0.15$ mmHg/compression; $p = 0.004$) over the course of the 20 post-interruption chest compressions.

Discussion

In this observational cohort study of pediatric IHCA, hemodynamics did not differ before and after interruptions in chest compressions. Blood pressure fell quickly and significantly during interruptions, but returned to pre-interruption baseline upon re-initiation of chest compressions rather than requiring several compressions to reach pre-interruption values as seen in laboratory data.[14] There were no differences in peri-interruption blood pressures between different age groups, cardiac arrest rhythms, timing or durations of interruptions, or patients with and without return of circulation. To our knowledge, this represents the first dedicated description of the hemodynamic impact of chest compression interruptions in the clinical setting during pediatric CPR. In this cohort of children with in-hospital resuscitation, brief interruptions in chest compressions (median 2.4 s) did not have a substantial effect on the post-interruption hemodynamics.

Sentinel laboratory studies on chest compression interruptions exhibited a significant drop in CoPP that persisted even after resuming chest compressions,[13,14] prompting our interest in studying this clinically. Importantly, these laboratory studies mimicked bystander CPR for adult out-of-hospital cardiac arrest. Chest compressions and ventilations were delivered in a 15:2 ratio with four-[14] or 16-s[13] interruptions for ventilations, simulating two-rescuer or single-rescuer CPR, respectively. Moreover, no vasopressors were administered in the initial 12 min of CPR, during which time the hemodynamic analyses were performed. In contrast, in this PICU study, 78% of children received at least one dose of epinephrine and 94% were invasively mechanically ventilated at the time of IHCA. Therefore, chest compressions were not routinely interrupted for ventilations, a likely driver for the median CCF of 95.3%. When interruptions did occur, they were brief — the median interruption duration was 2.4 s and the median duration of the longest interruption of each event was 9.6 s. Given these differences, our data should not be interpreted as standing in contrast to previously reported hemodynamic effects of chest compression interruptions, but rather that such detrimental effects can perhaps be avoided by optimization of CPR quality and minimization of the frequency and duration of the interruptions themselves.

The absence of a difference between pre- and post-interruption hemodynamics in this study is likely multifactorial. First, the interruptions in this cohort were rare and were brief, likely minimizing their hemodynamic effects. Of note, these findings were no different in the subgroup analysis among interruptions of at least five seconds in duration. Second, maintenance of arterial vascular tone with epinephrine during CPR likely tempers the effects of brief interruptions. Third, interruptions may facilitate resuscitation interventions, such as changes in compressors that can actually improve hemodynamics. Chest compression mechanics data were not available for this clinical cohort, but it is possible that higher quality chest compressions were delivered following interruptions due to the replacement of an ineffective manual compressor or due to an adjustment made by the existing compressor. This is particularly plausible since 57.1% of chest compression interruptions in our institution were reported to be due to compressor switches in previous work.[22] Additionally, SBP rose during the post-interruption period with SBP late post-interruption (compressions 18–20) being more than 12 mmHg higher than that measured early post-interruption (compressions 1–3). While not significantly higher than pre-interruption values ($p = 0.032$ with threshold for significance <0.0167 due to Bonferroni correction), this is similar to findings from a clinical study of five adult cardiac arrests[23] and could be explained by deeper compressions since SBP is associated with chest compression force and depth.[17] Finally, since all patients in this study had invasive arterial monitoring in place, rescuers may have titrated CPR to

Table 2 – Event characteristics.

Event characteristics (n = 32)	
Immediate cause of arrest, n (%)	
Hypotension	17 (53.1%)
Respiratory decompensation	11 (34.4%)
Arrhythmia	8 (25.0%)
First documented rhythm at time of CPR initiation, n (%)	
Asystole/PEA	13 (40.6%)
VF/pVT	7 (21.9%)
Bradycardia with poor perfusion	12 (37.5%)
Duration of CPR (min), median [IQR]	7.3 [2.6, 18.5]
CPR interventions, n (%)	
Epinephrine	25 (78.1%)
Number of epinephrine doses (when used), median [IQR]	3 [1,6]
Calcium	14 (43.8%)
Sodium bicarbonate	18 (56.3%)
Interventions in place at time of CPR, n (%)	
Central venous catheter	31 (96.9%)
Vasoactive infusion	27 (84.4%)
Invasive mechanical ventilation	30 (93.8%)
Noninvasive ventilation	2 (6.2%)
Interruptions, median [IQR]	
Number of interruptions per event	5 [1.5, 7.5]
Interruption duration (seconds)	2.4 [1.4, 7.0]
Time of first interruption (seconds, from CPR start)	51.7 [26.7, 104.4]
Duration of first interruption (seconds)	2.6 [1.5, 5.9]
Time of longest interruption (seconds, from CPR start)	112.8 [66.2, 308.6]
Order of longest interruption (number of interruption, from CPR start)	2.5 [1,4]
Duration of longest interruption (seconds)	9.6 [5.0, 16.6]
Chest compression fraction (% time, during first 10 min of CPR)	95.3 [86.8, 97.2]
Immediate outcome, n (%)	
Return of spontaneous circulation	23 (71.9%)
Return of circulation with ECMO	1 (3.1%)
Died	8 (25%)

CPR indicates cardiopulmonary resuscitation; PEA, pulseless electrical activity; VF, ventricular fibrillation; pVT, pulseless ventricular tachycardia; ECMO, extracorporeal membrane oxygenation.

hemodynamics and thereby proactively avoided interruption-related reductions in BPs. Given our PICU cardiac arrest debriefing program's focus on CPR physiology[24–26] and a research program focusing on the application of hemodynamic-directed CPR,[27,28] providers at our institution are likely to target hemodynamics when arterial BP data is available.

Similar to the aforementioned laboratory data demonstrating a reduction in DBP and CoPP with interruptions in chest compressions,[14] we observed an immediate fall in DBP of greater than 8 mmHg from the pre-interruption baseline upon discontinuation of compressions. This change occurred almost exclusively in the first second of the interruption, with minimal (-0.19 ± 0.02 mmHg/s) additional decrements over the subsequent course of each interruption. This demonstrates that even brief interruptions result in hemodynamic compromise during the course of the interruption itself. Additionally, after resuming chest compressions, there was a small but statistically significant rise in both DBP ($+0.13 \pm 0.06$ mmHg/compression) and SBP ($+0.42 \pm 0.15$ mmHg/compression) over the course of the first 20 chest compressions. This is suggestive of a hemodynamic impact that persists beyond the duration of the interruption itself but is tempered by other factors, such as deeper compressions or vasopressor effects. This finding is likely trivial in terms of clinical significance given the small magnitude of these changes coupled with the lack of difference between mean pre- and post-interruption blood pressures. It is possible that these findings would be of greater magnitude and of more substantial clinical significance in a cohort of patients with lower or more variable CPR quality or with lack of vasopressors.

The findings of this study add to a growing collection of literature questioning the standalone significance of interruptions and CCF on resuscitation outcomes. Despite the physiologically sound focus on minimizing "no-flow" time during CPR, multiple recent studies have either failed to show a relationship between CCF and outcomes or have actually demonstrated an inverse relationship between CCF and survival.[7,29–31] These studies are all limited by their observational nature, but their counterintuitive findings are worthy of consideration. It is likely that CCF and frequency and duration of interruptions are associated with other arrest characteristics that cannot be full-yaccounted for in statistical models. For example, patients with shockable rhythms requiring defibrillation or with identifiable arrest etiologies necessitating interruptions for intervention will have a tendency toward both improved outcomes and more interruptions.[7] Some studies have also identified a relationship between CCF and arrest duration,[31] which is itself associated with worse survival outcomes.[32] This is not surprising, as teams may become more effective at coordinating the choreography of CPR and thereby minimize interruptions in compressions as a cardiac arrest persists. Additionally, large animal laboratory studies introducing intentional, controlled interruptions in chest compressions ("stutter CPR") as a means of ischemic pre-conditioning have demonstrated neuro- and cardio-protection, and in some instances, hemodynamic benefit.[33,34] Nonetheless, the findings of the current study add physiologic validity to the assertion that brief and purposeful interruptions do not appear to impose substantial harm in the setting of high-quality CPR. Our data may inform clinicians regarding the risk-benefit ratio of interrupting CPR for specific reasons such as whether or not to tolerate brief interruptions for compressor switches to avoid fatigue or replace compressors delivering compressions of borderline quality. Monitoring peri-interruption hemodynamics and titrating both interruption duration and post-interruption CPR to a patient's physiologic response may also be a way to reduce the potential deleterious physiologic effects of interruptions.

This study has limitations. First, its observational nature limited our ability to understand the reasoning behind individual chest compression interruptions, which could impact hemodynamics. We did not control for vasopressor dosing or have chest compression mechanics data, both of which are likely confounders. Second, BP changes related to interruptions may underestimate changes in actual myocardial and cerebral blood flow, regarding which our ability to draw conclusions is limited. Thus, there may be detrimental hemodynamic effects of chest compression interruptions that cannot be ascertained through common clinical practices. Third, this is a report of a relatively small cohort of patients from a single institution with robust cardiac arrest research and resuscitation quality improvement programs. The patients included received high-quality CPR, as indicated by a CCF of >95%. They were also less likely to survive to hospital discharge compared to contemporary large children's hospital norms,[2] likely a result of the inclusion criteria of having invasive arterial monitoring in place and receiving at least one minute of CPR. Therefore, caution should be taken in applying these

Table 3 – Pre- versus post-interruption hemodynamics.

Variable	Pre-interruption value	Post-interruption value	p
Pre-[a] versus post-interruption[b]			
DBP (mmHg)	28.66 [21.59, 38.18]	28.31 [20.97, 37.38]	0.81
SBP (mmHg)	81.97 [51.73, 116.68]	85.42 [55.71, 122.24]	0.07
Pre-[a] versus early[c] post-interruption			
DBP (mmHg)	28.66 [21.59, 38.18]	28.06 [20.96, 37.71]	0.50
SBP (mmHg)	81.97 [51.73, 116.68]	77.87 [50.17, 119.29]	0.97
Pre-[a] versus intermediate[d] post-interruption			
DBP (mmHg)	28.66 [21.59, 38.18]	28.48 [20.71, 37.74]	0.95
SBP (mmHg)	81.97 [51.73, 116.68]	85.76 [55.73, 119.80]	0.023
Pre-[a] versus late[e] post-interruption			
DBP (mmHg)	28.66 [21.59, 38.18]	29.48 [21.78, 42.13]	0.14
SBP (mmHg)	81.97 [51.73, 116.68]	90.05 [64.67, 121.99]	0.032

DBP indicates diastolic blood pressure; SBP, systolic blood pressure. All comparisons made with Wilcoxon sign-rank test.
[a] Twenty chest compressions immediately preceding interruption.
[b] Twenty chest compressions immediately following interruption.
[c] Three chest compressions immediately following interruption.
[d] Chest compressions #9–11 following interruption.
[e] Chest compressions #18–20 following interruption.

findings to other clinical settings — the avoidance of unnecessary interruptions and maximization of CCF remain vital components of high-quality resuscitation. However, the study was facilitated and strengthened by the use of a high-fidelity hemodynamic data acquisition platform and novel waveform analytic process in place at our institution. Future work on this topic should include dedicated prospective laboratory work and observational clinical studies on a broader scale.

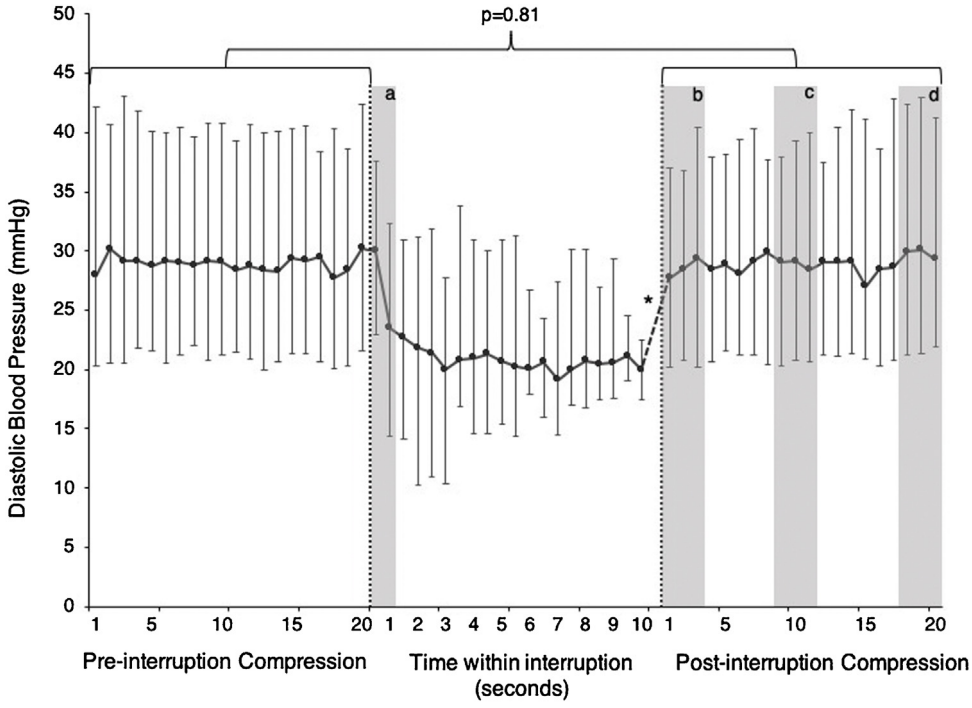

Fig. 3 – Peri-interruption diastolic blood pressures.
Diastolic blood pressures (DBP; median with interquartile range) over the course of the 20 pre- and post-interruption chest compressions and initial 10 s of the interruption. Later periods during interruption excluded due low number of events of sufficient duration. Vertical gray dotted lines indicate beginning and end of interruption. *Represents discontinuous data as interruptions were not exactly 10 s in duration. P-value for primary hemodynamic analysis shown (20 pre- versus 20 post-interruption compressions). Shaded gray areas indicate regions in which secondary analyses were performed: (a) first second of interruption (DBP: −8.41 mmHg/s, $p < 0.01$); (b) "early" post-interruption DBP (p = 0.50 versus pre-interruption DBP); (c) "intermediate" post-interruption DBP (p = 0.95 versus pre-interruption DBP); (d) "late" post-interruption DBP (p = 0.14 versus pre-interruption DBP). Wilcoxon sign-rank test used for pre- versus post-interruption analyses; linear regression used for intra-interruption DBP change estimation.

Conclusions

In this study, invasively measured BPs following short interruptions in chest compressions were not statistically different from those prior to interruptions. During interruptions, there was an immediate significant decrease in BP, especially in the first second. These data suggest that in the context of high-quality CPR with arterial monitoring in place, brief and purposeful chest compression interruptions do not have persistent negative hemodynamic impact.

Conflicts of interest

Financial support was provided through the Department of Anesthesiology and Critical Care Medicine at the Children's Hospital of Philadelphia.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resuscitation.2019.03.032.

REFERENCES

1. Knudson JD, Neish SR, Cabrera AG, et al. Prevalence and outcomes of pediatric in-hospital cardiopulmonary resuscitation in the United States: an analysis of the Kids' Inpatient Database. Crit Care Med 2012;40:2940–4.
2. Berg RA, Nadkarni VM, Clark AE, et al. Incidence and outcomes of cardiopulmonary resuscitation in PICUs. Crit Care Med 2016;44:798–808.
3. Girotra S, Spertus JA, Li Y, et al. Survival trends in pediatric in-hospital cardiac arrests: an analysis from Get With the Guidelines-Resuscitation. Circ Cardiovasc Qual Outcomes 2013;6:42–9.
4. Edelson DP, Abella BS, Kramer-Johansen J, et al. Effects of compression depth and pre-shock pauses predict defibrillation failure during cardiac arrest. Resuscitation 2006;71:137–45.
5. Christenson J, Andrusiek D, Everson-Stewart S, et al. Chest compression fraction determines survival in patients with out-of-hospital ventricular fibrillation. Circulation 2009;120:1241–7.
6. Cheskes S, Schmicker RH, Verbeek PR, et al. The impact of peri-shock pause on survival from out-of-hospital shockable cardiac arrest during the Resuscitation Outcomes Consortium PRIMED trial. Resuscitation 2014;85:336–42.
7. Wik L, Olsen JA, Persse D, et al. Why do some studies find that CPR fraction is not a predictor of survival? Resuscitation 2016;104:59–62.
8. Berg RA, Sutton RM, Reeder RW, et al. Association between diastolic blood pressure during pediatric in-hospital cardiopulmonary resuscitation and survival. Circulation 2018;137:1784–95.
9. Morgan RW, French B, Kilbaugh TJ, et al. A quantitative comparison of physiologic indicators of cardiopulmonary resuscitation quality: diastolic blood pressure versus end-tidal carbon dioxide. Resuscitation 2016;104:6–11.
10. Sanders AB, Kern KB, Atlas M, Bragg S, Ewy GA. Importance of the duration of inadequate coronary perfusion pressure on resuscitation from cardiac arrest. J Am Coll Cardiol 1985;6:113–8.
11. Meaney PA, Bobrow BJ, Mancini ME, et al. Cardiopulmonary resuscitation quality: [corrected] improving cardiac resuscitation outcomes both inside and outside the hospital: a consensus statement from the American Heart Association. Circulation 2013;128:417–35.
12. de Caen AR, Berg MD, Chameides L, et al. Part 12: Pediatric Advanced Life Support: 2015 American Heart Association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2015;132:S526–42.
13. Kern KB, Hilwig RW, Berg RA, Sanders AB, Ewy GA. Importance of continuous chest compressions during cardiopulmonary resuscitation: improved outcome during a simulated single lay-rescuer scenario. Circulation 2002;105:645–9.
14. Berg RA, Sanders AB, Kern KB, et al. Adverse hemodynamic effects of interrupting chest compressions for rescue breathing during cardiopulmonary resuscitation for ventricular fibrillation cardiac arrest. Circulation 2001;104:2465–70.
15. Jacobs I, Nadkarni V, Bahr J, et al. Cardiac arrest and cardiopulmonary resuscitation outcome reports: update and simplification of the Utstein templates for resuscitation registries. A statement for healthcare professionals from a task force of the international liaison committee on resuscitation (American Heart Association, European Resuscitation Council, Australian Resuscitation Council, New Zealand Resuscitation Council, Heart and Stroke Foundation of Canada, InterAmerican Heart Foundation, Resuscitation Council of Southern Africa). Resuscitation 2004;63:233–49.
16. Sutton RM, Reeder RW, Landis W, et al. Chest compression rates and pediatric in-hospital cardiac arrest survival outcomes. Resuscitation 2018;130:159–66.
17. Sutton RM, French B, Nishisaki A, et al. American Heart Association cardiopulmonary resuscitation quality targets are associated with improved arterial blood pressure during pediatric cardiac arrest. Resuscitation 2013;84:168–72.
18. Niles DE, Duval-Arnould J, Skellett S, et al. Characterization of pediatric in-hospital cardiopulmonary resuscitation quality metrics across an international resuscitation collaborative. Pediatr Crit Care Med 2018;19:421–32.
19. Meaney PA, Nadkarni VM, Cook EF, et al. Higher survival rates among younger patients after pediatric intensive care unit cardiac arrests. Pediatrics 2006;118:2424–33.
20. Nadkarni VM, Larkin GL, Peberdy MA, et al. First documented rhythm and clinical outcome from in-hospital cardiac arrest among children and adults. JAMA 2006;295:50–7.
21. Fiser DH. Assessing the outcome of pediatric intensive care. J Pediatr 1992;121:68–74.
22. Sutton RM, Maltese MR, Niles D, et al. Quantitative analysis of chest compression interruptions during in-hospital resuscitation of older children and adolescents. Resuscitation 2009;80:1259–63.
23. Hoppu S, Sainio M, Huhtala H, Eilevstjonn J, Tenhunen J, Olkkola KT. Blood pressure during resuscitation in man — the effect of pause during rhythm analysis revisited. Resuscitation 2011;82:1460–3.
24. Wolfe H, Zebuhr C, Topjian AA, et al. Interdisciplinary ICU cardiac arrest debriefing improves survival outcomes. Crit Care Med 2014;42:1688–95.
25. Wolfe H, Maltese MR, Niles DE, et al. Blood pressure directed booster trainings improve intensive care unit provider retention of excellent cardiopulmonary resuscitation skills. Pediatr Emerg Care 2015;31 (11):743–7.
26. Reeder RW, Girling A, Wolfe H, et al. Improving outcomes after pediatric cardiac arrest - the ICU-Resuscitation Project: study protocol for a randomized controlled trial. Trials 2018;19:213.
27. Morgan RW, Kilbaugh TJ, Shoap W, et al. A hemodynamic-directed approach to pediatric cardiopulmonary resuscitation (HD-CPR) improves survival. Resuscitation 2016;111:41–7.
28. Sutton RM, Friess SH, Naim MY, et al. Patient-centric blood pressure-targeted cardiopulmonary resuscitation improves survival from cardiac arrest. Am J Respir Crit Care Med 2014;190:1255–62.
29. Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. Resuscitation 2017;116:60–5.
30. Cheskes S, Schmicker RH, Rea T, et al. The association between AHA CPR quality guideline compliance and clinical outcomes from out-of-hospital cardiac arrest. Resuscitation 2017;116:39–45.

31. Cheskes S, Schmicker RH, Rea T, et al. Chest compression fraction: a time dependent variable of survival in shockable out-of-hospital cardiac arrest. Resuscitation 2015;97:129–35.
32. Matos RI, Watson RS, Nadkarni VM, et al. Duration of cardiopulmonary resuscitation and illness category impact survival and neurologic outcomes for in-hospital pediatric cardiac arrests. Circulation 2013;127:442–51.
33. Bartos JA, Matsuura TR, Sarraf M, et al. Bundled postconditioning therapies improve hemodynamics and neurologic recovery after 17 min of untreated cardiac arrest. Resuscitation 2015;87:7–13.
34. Matsuura TR, Bartos JA, Tsangaris A, et al. Early effects of prolonged cardiac arrest and ischemic postconditioning during cardiopulmonary resuscitation on cardiac and brain mitochondrial function in pigs. Resuscitation 2017;116:8–15.