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Clinical paper

The association of arterial blood pressure waveform-derived area duty cycle with intra-arrest hemodynamics and cardiac arrest outcomes

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Abstract

Aim: Develop a novel, physiology-based measurement of duty cycle (Arterial Blood Pressure–Area Duty Cycle [ABP–ADC]) and evaluate the association of ABP–ADC with intra-arrest hemodynamics and patient outcomes.

Methods: This was a secondary retrospective study of prospectively collected data from the ICU-RESUS trial (NCT02837497). Invasive arterial waveform data were used to derive ABP–ADC. The primary exposure was ABP–ADC group (<30%; 30–35%; >35%). The primary outcome was systolic blood pressure (sBP). Secondary outcomes included intra-arrest physiologic goals, CPR quality targets, and patient outcomes. In an exploratory analysis, adjusted splines and receiver operating characteristic (ROC) curves were used to determine an optimal ABP–ADC associated with improved hemodynamics and outcomes using a multivariable model.

Results: Of 1129 CPR events, 273 had evaluable arterial waveform data. Mean age is 2.9 years + 4.9 months. Mean ABP–ADC was 32.5% + 5.0%. In univariable analysis, higher ABP–ADC was associated with lower sBP ($p < 0.01$) and failing to achieve sBP targets ($p < 0.01$). Other intra-arrest physiologic parameters, quality metrics, and patient outcomes were similar across ABP–ADC groups. Using spline/ROC analysis and clinical judgement, the optimal ABP–ADC cut point was set at 33%. On multivariable analysis, sBP was significantly higher (point estimate 13.18 mmHg, CI95 5.30–21.07, $p < 0.01$) among patients with ABP–ADC < 33%. Other intra-arrest physiologic and patient outcomes were similar.**Conclusions**: In this multicenter cohort, a lower ABP–ADC was associated with higher sBPs during CPR. Although ABP–ADC was not associated with outcomes, further studies are needed to define the interactions between CPR mechanics and intra-arrest patient physiology.

Keywords: Cardiac Arrest, Cardiopulmonary Resuscitation, Pediatrics

Introduction

Approximately 15,000 children receive cardiopulmonary resuscitation (CPR) for in-hospital cardiac arrest (p-IHCA) every year in the United States.[1–3] Guidelines recommend targeting specific CPR quality mechanics for chest compression depth, rate, and fraction, and ventilation.[4] While these particular aspects of pediatric CPR are the most well-studied, other compression characteristics such as duty cycle (DC) - the percentage of time in the downward phase of a chest compression (effective compression time [ECT]) – are less understood and may represent an opportunity to improve outcomes.[5]

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To that end, pre-clinical data suggest that DC can be optimized to improve intra-arrest hemodynamics.[6,7] However, clinical studies of this parameter during in-hospital resuscitations have been limited. A previous single-center cohort study in 87 children found DC to be associated with chest compression rate, but not with intra-arrest hemodynamics or outcomes.[8] Given the established relationships between intra-arrest hemodynamics and outcomes in children,[9,10] further investigation is warranted.

To fill this knowledge gap, we conducted a secondary analysis of data from the ICU-RESUScitation Project (*ICU-RESUS*; NCT02837497), a prospective multicenter randomized trial of physiologic-directed CPR training and debriefing for p-IHCA. Using a novel invasive arterial blood pressure-derived definition of duty cycle (Arterial Blood Pressure-Area Duty Cycle [ABP–ADC]), the objectives of this study were to: (1) quantitatively describe ABP–ADC in a large multicenter cohort and (2) to determine the association between ABP–ADC and intra-arrest hemodynamics and patient outcomes.

Methods

Study design and setting

This was a secondary retrospective study of prospectively collected data from the *ICU-RESUS* trial, a hybrid stepped-wedge cluster-randomized trial from 18 pediatric and pediatric cardiac intensive care units (ICUs) at ten clinical sites in the United States. The *ICU-RESUS* intervention was a CPR quality improvement bundle of physiologic-directed point-of-care CPR training and debriefing.[11] Patients in the *ICU-RESUS* trial were enrolled from October 1, 2016 through March 31, 2021. The central institutional review board (IRB) at the University of Utah granted a waiver of informed consent. More details can be found in the previously published trial description and in the trial results.[11,12]

Patient population

Patients ≤ 18 years of age and ≥37 weeks corrected gestational age who received chest compressions of any duration while admitted to the ICU were included. Main trial exclusion criteria have been previously published.[11,12] Specifically for this analysis that required arterial line waveform data, patients were excluded if they did not have an invasive arterial catheter at the start of CPR or did not have sufficient waveform data quality to determine when CPR started/stopped or to calculate ABP–ADC. Because CPR method, chest wall dynamics, and as a result, the relationship between ABP–ADC and outcomes, are likely different in patients with open chests, these patients were also excluded.

Data collection

Cardiac arrest data element collection was consistent with the Utstein Resuscitation Registry Template for In-Hospital Cardiac Arrest.[13,14] As previously described in the *ICU-RESUS* trial,[12] site coordinators downloaded bedside monitor waveform data to be reviewed and analyzed by blinded investigators (RWM, KG, RMS).[10,15]

Arterial Blood Pressure – Area Duty Cycle (ABP–ADC) calculation

Area duty cycle (ADC) has been previously used to describe DC during adult cardiac arrest resuscitations.[16] The method is calculated as the ratio of the area under the force waveform curve (i.e., during positive deflection) to the total area of the entire compression-decompression cycle. While previous work focused on compression force, invasive arterial line waveforms were used in a similar fashion in this investigation to calculate ABP–ADC (Fig. 1). MATLAB (The MathWorks, Inc.) was used to calculate ABP–ADC for each compression.

Outcomes and statistical analysis

The primary exposure for the univariable analysis was event-level ABP–ADC defined as the mean ABP–ADC over the first 10 minutes of the CPR event. Patients were *a priori* divided into ABP–ADC tertiles which were approximated by the following three groups: <30%, 30–35%, and >35% for the primary analyses. The primary outcome was mean systolic blood pressure (sBP), chosen based upon pre-clinical data showing a strong association between duty cycle and sBP.[17]

Secondary physiologic and intra-arrest CPR mechanics outcomes included: mean diastolic blood pressure (dBP); end-tidal carbon dioxide ($ETCO_2$); chest compression depth (mm); chest compression rate; and chest compression fraction (CCF). Secondary patient outcomes included: return of spontaneous circulation (ROSC); survival to hospital discharge; and survival to hospital discharge with favorable neurologic outcome, defined as a Pediatric Cerebral Performance Category (PCPC) score of 1–3 (no more than moderate disability) or no worsening from pre-hospitalization baseline.[13,18] Among survivors, additional secondary outcomes included Functional Status Scale (FSS) and new morbidity (≥3-point increase in FSS), again comparing pre-hospitalization baseline to hospital discharge.[19]

Patient characteristics, event characteristics, intra-arrest physiology and mechanics, and clinical outcomes were summarized using counts and percentages. Associations of these variables with ABP–ADC group (<30%, 30–35%, >35%) were evaluated with the Jonckheere-Terpstra test for continuous and ordinal variables, the Cochrane-Armitage trend test for binary variables, and the Kruskal-Wallis test for other categorical (nominal) variables. These tests were chosen because they account for the ordered nature of the ABP–ADC groups. Summaries and analyses were performed in the entire cohort (primary analysis) and in age subgroups (<1 year, ≥1 year).

Determination of optimal ABP–ADC

To identify an optimal ABP–ADC target/range for sBP during CPR, receiver operator characteristics (ROC) and adjusted spline curves were created. For ROC curve analyses, a binary outcome termed adequate systolic blood pressure was defined as ≥60 mmHg for age <1 year and ≥80 mmHg for age ≥1 year. For the spline analysis, natural cubic splines with internal knots at the 10th, 50th, and 90th percentiles were used to adequately capture the relationship between ABP–ADC and sBP without overfitting. ROC curves (target based on Euclidian distance)/splines and clinical judgement were used to define an optimal ABP–ADC target/range for sBP. Patients were then dichotomized according to ABP–ADC as either below the target/range or greater than or equal to the target/range. The association of this target with intra-arrest physiology, mechanics, and clinical outcomes was further evaluated with multivariable linear regression models for continuous variables and with multivariable Poisson regression models with robust error estimates for binary variables. Each variable was modeled separately, and all models controlled for age (<1 year, ≥1 year), vasoactive infusion at the start of CPR (yes, no), and respiratory decompensation as an immediate cause of arrest (yes, no). Covariates were selected *a priori*. Analyses

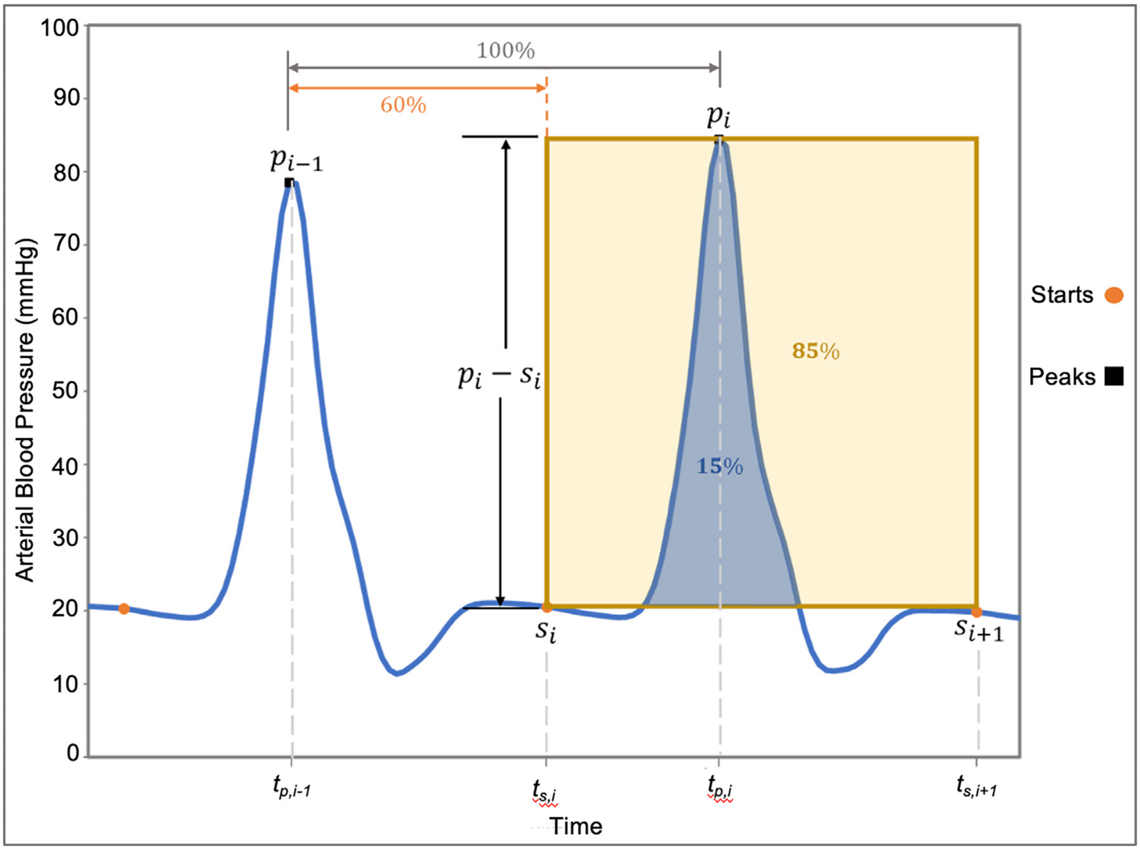

Fig. 1 – ABP–ADC Beat-to-beat Calculation. For each chest compression cycle, i, the peak arterial blood pressure value, p_i, which takes place at the peak time $t_{p,i}$, corresponds to the systolic blood pressure. The start time for the compression cycle was similarly determined. The start time $t_{s,i}$ for compression i was 60% between the peak time $t_{p,i}$ of compression cycle i and the peak time of compression cycle $i-1$, $t_{p,i-1}$, as shown in Eq. (1): $t_{s,i} = t_{p,i-1} + 0.6 * (t_{p,i} - t_{p,i-1})$ The arterial waveform for one compression cycle was bounded by the compression's start point $t_{s,i}$ and peak p_i and with the start time of the next compression $t_{s,i+1}$. The cycle height was $p_i - s_i$ and the width was $t_{s,i+1} - t_{s,i}$. With the rectangle generated by these coordinates, ABP–ADC was calculated by summing the area under the ABP waveform and dividing by the total rectangular area: $ADC_i = \frac{\sum_{t_{s,i}}^{t_{s,i+1}} \max((ABP(t) - s_i), 0)\Delta t}{(p_i - s_i) * (t_{s,i+1} - t_{s,i})}$.

were performed in SAS 9.4 (SAS Institute; Cary, NC). P-values were based on a 2-sided alternative and considered significant if <0.05.

Results

Events and patients

Of 413 patients with arterial blood pressure tracings available, 273 index events were included in the final analysis (Supplementary Fig. 1s). This consisted of 148,687 analyzable chest compressions from 3,112 30-second data epochs.

Descriptive statistics and primary outcome

The mean ABP–ADC of all events was 32.5% ± 5.0% with an overall range of 18.7–46.2%. See Fig. 2 for a histogram of ABP–ADC for the entire cohort. Demographic data are summarized in Table 1, and cardiac arrest event data are shown in Supplemental Table 1s. Age and pre-existing conditions of sepsis and congenital heart disease were significantly different across ABP–ADC groups. There were significant differences in sBP across ABP–ADC groups (<30%: 96 mmHg; 30–35%: 82 mmHg; >35%: 72 mmHg [$p < 0.01$]). Similarly, a higher percentage of patients in the lower ABP–ADC group achieved predefined intra-arrest sBP targets ($p = 0.01$). The statistically significant association between ABP–ADC and sBP was seen in infants <1 year old ($p < 0.01$), with a lower ABP–ADC being associated with higher sBP. For older children, there was a similar association; however, the ABP–ADC > 35% had a higher sBP than the 30–35% group (Supplemental Table 2s).

Secondary outcomes

Among the entire cohort and in patients <1 year of age, mean dBP was not different across groups; however, the percentage of patients achieving the *a priori* dBP target was significantly higher in patients with a higher ABP–ADC. Other intra-arrest physiologic measures, CPR quality mechanics, and patient outcomes were not different across ABP–ADC groups (Table 2). Similarly, there were no associations in subgroup analyses of infants and older children (Supplemental Table 2s).

Determination of optimal ABP–ADC for sBP

ROC analysis identified an optimal ABP–ADC target <31.2% for sBP based on Euclidian Distance (Supplemental Fig. 2s). To provide a

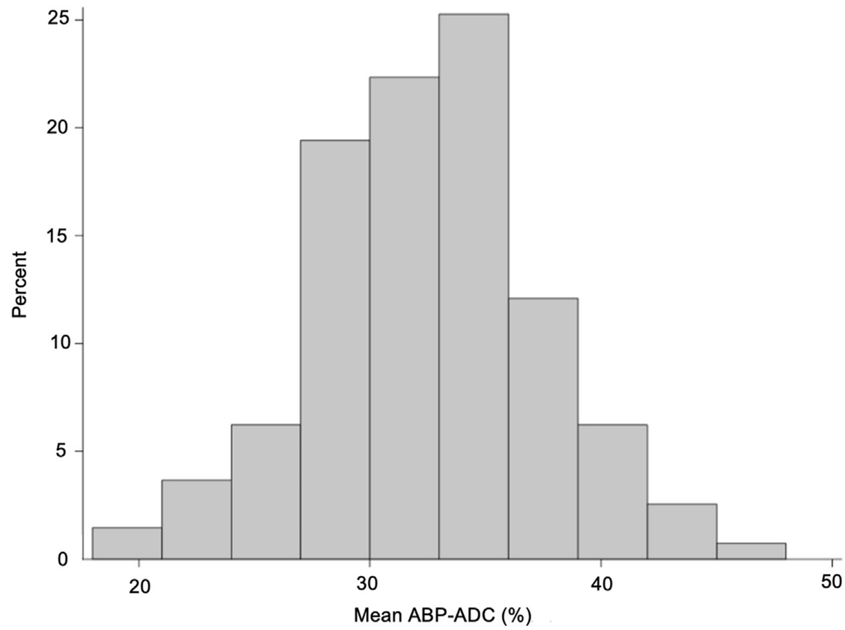

Fig. 2 – Distribution of Arterial Blood Pressure – Area Duty Cycle (ABP–ADC) for each CPR event.

Table 1 – Patient demographic and pre-cardiac arrest medical conditions.

Characteristic	ABP–ADC <30%(N = 84)	ABP–ADC 30–35%(N = 110)	ABP–ADC >35%(N = 79)	*P*-value
Demographics				
Age				0.004
<1 month	18 (21.4%)	29 (26.4%)	24 (30.4%)	
1 month–<1 year	19 (22.6%)	52 (47.3%)	32 (40.5%)	
1 year–<12 years	35 (41.7%)	22 (20.0%)	16 (20.3%)	
>12 years	12 (14.3%)	7 (6.4%)	7 (8.9%)	
Male	44 (52.4%)	57 (51.8%)	44 (55.7%)	0.677
Race				0.713
White	42 (50.0%)	53 (48.2%)	37 (46.8%)	
Black or African American	16 (19.0%)	23 (20.9%)	17 (21.5%)	
Other	4 (4.8%)	9 (8.2%)	6 (7.6%)	
Unknown or Not Reported	22 (26.2%)	25 (22.7%)	19 (24.1%)	
Hispanic or Latino	14 (16.7%)	13 (11.8%)	10 (12.7%)	0.553
Preexisting medical conditions				
Respiratory insufficiency	72 (85.7%)	88 (80.0%)	65 (82.3%)	0.553
Hypotension	67 (79.8%)	79 (71.8%)	65 (82.3%)	0.727
Congestive heart failure	10 (11.9%)	12 (10.9%)	5 (6.3%)	0.237
Pneumonia	8 (9.5%)	13 (11.8%)	6 (7.6%)	0.693
Sepsis	21 (25.0%)	7 (6.4%)	8 (10.1%)	0.004
Trauma	1 (1.2%)	2 (1.8%)	1 (1.3%)	0.962
Renal insufficiency	6 (7.1%)	10 (9.1%)	7 (8.9%)	0.689
Malignancy	7 (8.3%)	2 (1.8%)	6 (7.6%)	0.803
Pulmonary hypertension	16 (19.0%)	15 (13.6%)	10 (12.7%)	0.250
Congenital heart disease	52 (61.9%)	77 (70.0%)	61 (77.2%)	0.034

ABP–ADC indicates Arterial Blood Pressure – Area Duty Cycle.
The Kruskal-Wallis test was used for categorical (nominal) variables. The Cochrane-Armitage trend test was used for binary variables.

more feasible target, clinician judgement, in combination with statistical fit, was used to select an optimal ABP–ADC for sBP of <33% (i.e., 1/3 of the total compression cycle) to be used in subsequent multivariable models. Systolic blood pressure was significantly higher among patients with an ABP–ADC below this clinical target compared to those with higher ABP–ADC (point estimate: 13 mmHg, CI95 5.30 to 21.07, $p < 0.01$). Survival outcomes were not different for patients who received an ABP–ADC less than versus greater-

Table 2 – Intra-arrest physiologic targets and chest compression mechanics.

Measure	ABP–ADC <30% (N = 37)	30–35% (N = 81)	>35% (N = 56)	P-value
ABP–ADC (%)	28 [25,29]	33 [31,34]	38 [36,40]	
Primary Outcome				
Systolic blood pressure (mmHg)	96 [80,124]	82 [61,101]	72 [57,90]	<0.001
Adequate systolic blood pressure*	69/84 (82.1%)	78/110 (70.9%)	47/78 (60.3%)	0.002
Secondary Outcomes				
Hemodynamics				
Diastolic blood pressure (mmHg)	42 [32,51]	39 [31,49]	40 [33,52]	0.785
Adequate diastolic blood pressure†	70/84 (83.3%)	97/110 (88.2%)	74/79 (93.7%)	0.040
Mechanics				
Chest compression rate	120 [113,126]	120 [110,134]	123 [117,133]	0.081
Chest compression rate between 90 and 130 (per minute)	68/84 (81.0%)	75/110 (68.2%)	57/79 (72.2%)	0.194
Chest compression fraction over the first 10 minutes	0.96 [0.91,1.00]	0.98 [0.92,1.00]	0.97 [0.93,1.00]	0.895
Chest compression fraction ≥90%	64/84 (76.2%)	89/110 (80.9%)	65/79 (82.3%)	0.329
Depth ≥40 mm for age <1 year or ≥50 mm for age ≥1 year	6/22 (27.3%)	2/20 (10.0%)	1/10 (10.0%)	0.153
Depth (mm)	33 [22,67]	27 [22,40]	29 [26,43]	0.733
Ventilation				
End-tidal CO2 (mmHg)	21 [13,31]	21 [14,29]	22 [13,27]	0.975
End-tidal CO2 ≥ 20 mmHg	20/37 (54.1%)	28/53 (52.8%)	19/32 (59.4%)	0.672
Ventilation rate (breaths/min) during compressions	25 [20,37]	29 [25,36]	26 [20,30]	0.778
Ventilation rate 8–12 breaths/min during compressions	0/37 (0%)	0/53 (0%)	0/32 (0%)	

ABP–ADC indicates Arterial Blood Pressure – Area Duty Cycle.
The Jonckheere-Terpstra test was used for continuous and ordinal variables.
The Cochrane-Armitage trend test was used for binary variables.
* Average systolic BP of ≥60 mmHg for age <1 year or ≥80 mmHg for age ≥1 year.
† Average diastolic BP of ≥25 mmHg for age <1 year or ≥30 mmHg for age ≥1 year.

Table 3 – Clinical outcomes.

Outcome	ABP–ADC <30% (N = 84)	30–35% (N = 110)	>35% (N = 79)	P-value
ROSC ≥ 20 minutes	60 (71%)	78 (71%)	54 (68%)	0.670
Survival to hospital discharge	50 (60%)	74 (67%)	46 (58%)	0.886
Survival to hospital discharge with favorable neurologic outcome†	45 (54%)	71 (65%)	46 (58%)	0.527
Total FSS at hospital discharge	8 [7,10]	8 [6,11]	8 [6,10]	0.482
PCPC at hospital discharge				0.508
1 – Normal	21 (25%)	41 (37%)	25 (32%)	
2 – Mild disability	15 (18%)	17 (15%)	15 (19%)	
3 – Moderate disability	8 (10%)	10 (9%)	5 (6%)	
4 – Severe disability	6 (7%)	5 (5%)	1 (1%)	
5 – Coma/vegetative state	0 (0%)	1 (1%)	0 (0%)	
6 – Death	34 (40%)	36 (33%)	33 (42%)	
Change from baseline to hospital discharge in functional status (FSS) of survivors	2 [0, 4]	2 [0, 3]	2 [0, 3]	0.888
New morbidity‡ (survivors only)	17 (34%)	21 (28%)	15 (33%)	0.868

ABP–ADC indicates Arterial Blood Pressure – Area Duty Cycle; ROSC, return of spontaneous circulation; FSS, Functional Status Scale; PCPC, Pediatric Cerebral Performance Category.
† Favorable neurologic outcome is defined as no more than moderate disability or no worsening from baseline Pediatric Cerebral Performance Category (PCPC).
‡ New morbidity among survivors is defined as a worsening from baseline FSS by 3 points or more.

than-or-equal to 33%. (Table 3). However, patients with an ABP–ADC less than 33% had lower relative risk of average dBP meeting specified age thresholds (RR 0.91, CI95 0.84–0.99, p = 0.028) and average ETCO2 ≥ 20 mmHg (RR 0.67, CI95 0.49–0.92, p = 0.013) (Table 4).

Discussion

To our knowledge this was the first multicenter report of pediatric DC as determined by arterial blood pressure waveforms during resuscitation attempts of children with IHCA. We found that the mean

Table 4 – Association of optimal ABP–ADC 33% with physiologic, mechanic, and clinical outcomes.*

Measure	Mean difference(95% CI)	Relative risk(95% CI)	*P*-value
Primary Outcome			
Average systolic blood pressure (mmHg)	13.18 (5.30, 21.07)		0.001
Adequate systolic blood pressure[†]		1.16 (1.00, 1.35)	0.053
Secondary Outcomes			
Hemodynamics			
Average diastolic blood pressure (mmHg)	−2.89 (−6.76, 0.99)		0.144
Adequate diastolic blood pressure[‡]		0.91 (0.84, 0.99)	0.028
Mechanics			
Average chest compression rate over the first 10 minutes	−2.25 (−6.18, 1.69)		0.261
Average chest compression rate between 90 and 130 (per minute)		1.03 (0.89, 1.19)	0.701
Average chest compression fraction over the first 10 minutes	−0.00 (−0.02, 0.02)		0.920
Average chest compression fraction $\geq$90%		0.96 (0.86, 1.08)	0.509
Average depth (mm)	2.21 (−9.10, 13.52)		0.697
Ventilation			
Average end-tidal CO_2 (mmHg) during compressions	−3.36 (−7.04, 0.32)		0.073
Average end-tidal $CO_2 \geq$ 20 mmHg during compressions		0.67 (0.49, 0.92)	0.013
Average ventilation rate (breaths/min) during compressions	0.77 (−3.29, 4.84)		0.708
Clinical outcomes			
ROSC $\geq$ 20 minutes		1.05 (0.90, 1.23)	0.539
Survival to hospital discharge		1.04 (0.86, 1.25)	0.692
Survival to hospital discharge with favorable neurologic outcome[#]		0.97 (0.80, 1.18)	0.793

ABP–ADC indicates Arterial Blood Pressure – Area Duty Cycle; ROSC, return of spontaneous circulation.

* 33% ABP–ADC was used instead of optimal ROC and Spline curve derived cut point of 31.2% given its proximity to the cut point and more interpretable meaning.

† Average systolic BP of $\geq$60 mmHg for age <1 year or $\geq$80 mmHg for age $\geq$1 year.

‡ Average diastolic BP of $\geq$25 mmHg for age <1 year or $\geq$30 mmHg for age $\geq$1 year.

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

ABP–ADC delivered was uniformly lower than the currently recommended ECT DC of 50%.[5,8,16,20] A lower ABP–ADC was associated with higher sBP during CPR. This association held in a multivariable model for those who received an ABP–ADC less than the derived clinical cut point (33%) after controlling for age, vasopressor support at time of arrest, and respiratory decompensation as an immediate cause of arrest. To our surprise, ABP–ADC below the derived 33% cut point was associated with lower relative risk of attaining established dBP targets[10] or ETCO2 $\geq$ 20 mmHg – a finding that was in contrast to prior pre-clinical work.[6,7] Lower ABP–ADC was not associated with patient outcomes in multivariable models.

Similar to prior adult and pediatric investigations of mechanical DC, the ABP–ADC delivered in our study was below the current AHA recommended target of 50%. In fact, despite our cohort's range (18.7–46.2%), no single child had an ABP–ADC of 50% or higher. In the single-center pediatric study of DC by Wolfe et al., which used an ECT method, the mean DC was 40.1%, and similarly, no child received a DC of 50% or higher.[8] The difference of 7.6% between our investigation and this prior pediatric work is likely due to known differences between calculation methods (i.e., ECT vs. AUC method). To that end, Johnson et al. similarly found a difference of 6.6% when comparing ECT DC and an AUC method on the same cohort of adult patients.[16] Although previous work identified a relationship between DC and compression rate,[8] the association between ABP–ADC and compression rate was not significant in our analysis. This is the first clinical study to suggest that a shorter DC has intraarrest hemodynamic impacts.

Our observation that a lower ABP–ADC is associated with greater sBP is consistent with our hypothesis derived from preclinical studies.[21] First, a lower ABP–ADC with a constant chest compression rate allows for more ventricular filling time, and as a result, a greater volume of blood will be ejected during the chest compression, generating higher peak intravascular pressure. Second, a lower ABP–ADC (i.e., a chest compression with rapid downstroke) mimics increased heart contractility, potentially leading to a higher ejection fraction causing a higher intravascular pressure.

When comparing patients with ABP–ADC below versus above the identified optimal threshold for sBP (33%), we identified seemingly contradictory findings regarding dBP and ETCO2. Namely, patients with lower ABP–ADC less frequently met the dBP and ETCO2 thresholds that are recommended to gauge CPR quality. Though observed differences in average dBP and ETCO2 were modest and did not reach statistical significance, the discordance of sBP and dBP in terms of their relationship with DC deserves comment. One physiologic explanation for this may be a subset of patients with poor vascular tone benefitting from a higher ABP–ADC and briefer period of inter-compression "diastole," allowing less diastolic runoff (with rate being held constant), and therefore higher dBP. This significant difference may have not translated into clinical outcomes because over 80% of our cohort achieved dBP targets, and there was only a 14 percentage-point spread between the shortest and longest ABP–ADC groups achieving the dBP goal. In short, we were underpowered to detect a difference in outcomes related to dBP and ABP–ADC. In addition, it is notable that preclinical studies found improved dBP with lower (30%) compared to much higher (50%) ECT.[6,22,23] In contrast, although our cohort had a similar range, there were not enough patients at either end of the range to evaluate if one extreme was better as done in preclinical studies. Thus, future laboratory and clinical studies should further investigate potential mechanisms behind these observations and their impact with organ perfusion, resuscitation success, and clinical outcomes.

As previously stated, prior investigations of DC utilized force tracings, not ABP tracings. As such, ABP–ADC represents not only the mechanical effects of CPR, but also the patient's individual, dynamic physiology – a distinct difference from prior work necessary to interpret and apply our findings. While ABP–ADC as a "waveform characteristic" is consistent with the large body of evidence suggesting that arterial pressure waveforms can be used to gain insight into a patient's cardiovascular system,[24–26] the clinical utility of such a metric deserves comment. As a specific example, sepsis as a pre-existing condition was associated with a lower ABP–ADC. The lower ABP–ADC in these patients may be partly due to a more rapid decrement in ABP after chest compression due to poor vascular tone (i.e., low systemic vascular resistance). In these cases, other interventions (e.g., vasopressor administration) may be necessary to improve chances of successful resuscitation. Congenital heart disease as a pre-existing condition was also associated with ABP–ADC tertile, with this group characterized by receiving a higher ABP–ADC. In contrast to sepsis, we anticipate that this finding was driven by infants being more represented in this group, rather than any specific patient or physiologic factor.

To that end, the association between ABP–ADC and age deserves comment – neonates and infants were more represented in higher ABP–ADC tertiles and older children in the lowest tertile. These observed associations could be due to inherent differences in chest wall mechanics in younger children resulting in slower chest wall recoil and a higher ABP–ADC.[27] Alternatively, CPR technique (i.e., 2-thumb-encircling hands technique or 2-finger technique in infants vs. the 1- or 2-hand technique in older children[4]) may contribute to delayed or incomplete release by rescuers and a resultant higher ABP–ADC. As our study did not include data regarding chest compression techniques, these relationships could not be addressed but deserve examination in future work.

Finally, the "inability" to achieve current DC recommendations in both these data and in prior work[8] deserves comment. Taken together, these studies raise the question, "Should the recommended DC goal be changed?" There is a large body of preclinical evidence demonstrating that titration of CPR technique to optimize hemodynamics improves outcomes.[28,29] We believe that "optimal" DC will therefore be best defined as the range/target that improves established intra-arrest physiologic targets associated with improved outcomes (e.g., diastolic blood pressure[9] or ETCO2[30]), rather than a set target that applies to all patients. However, we caution the reader against focusing on DC to achieve hemodynamic goals over more well-established metrics such as timely administration of vasopressors[31,32] and high-quality CPR.[12,33] In the end, these data simply highlight DC as a potential "adjunct" factor to be adjusted when physiologic goals are not achieved through more proven methods.

Our study had limitations. This was an observational study design. As such, we could not assign causation between ABP–ADC and the hemodynamic outcomes. Second, we were only able to study the ABP–ADC delivered to our patients in the course of clinical care and this was a relatively narrow range. No patients received ABP–ADC higher than the 50% ECT DC recommended by guidelines; such DC may be harmful, but this could not be assessed. Third, the parent *ICU-RESUS* trial utilized accelerometer-based CPR quality recording devices. This technology, in contrast to prior pediatric work which utilized devices with force transducers, does not record/report DC. As such, the relationship between ECT DC as calculated from applied force waveforms[8,16] and ABP–ADC remains unknown – an area ripe for future investigation given that only 50% of patients will have the necessary invasive monitoring to calculate ABP–ADC.[34] Fourth, due to a paucity of available right atrial or central venous pressure values, we were unable to calculate coronary perfusion pressure and determine the association of ABP–ADC with this important determinant of myocardial blood flow and resuscitation success.[35] Finally, generalizability may be a concern given the *ICU-RESUS* study was conducted in a network of hospitals with a specific interest in resuscitation quality improvement. However, it is notable that even in this cohort – as in other care settings – adherence to some evidence-based practice guidelines (e.g., ventilation rate compliance) remains difficult.

Conclusions

In this multicenter observational cohort of pediatric IHCA, the delivered ABP–ADC was significantly lower than currently recommended duty cycle in CPR guidelines. Values of ABP–ADC below the clinical target identified in this cohort (33%) were associated with higher sBP but not patient outcomes.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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