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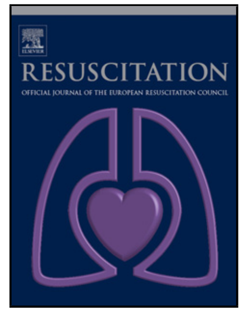

Analysis of CPR quality by individual providers in the pediatric emergency department

Aaron J. Donoghue MD, MSCE Sage Myers MD, MSCE Benjamin Kerrey MD, MS Alexis Sandler Ryan Keane Ichiro Watanabe MD Richard Hanna Mary Kate Abbadessa MSN, RN Mary Frey MSN Karen O'Connell MD, MEd

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Aaron J. Donoghue, MD, MSCE[1,2], Sage Myers, MD, MSCE[1], Benjamin Kerrey, MD, MS[3], Alexis Sandler[4], Ryan Keane[5], Ichiro Watanabe, MD[6], Richard Hanna[1], Mary Kate Abbadessa, MSN, RN[2], Mary Frey, MSN[3], Karen O'Connell, MD, MEd[7]

Affiliations:
[1]Division of Critical Care Medicine, Department of Anesthesia and Critical Care Medicine, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, PA
[2]Division of Emergency Medicine, Department of Pediatrics, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, PA
[3]Division of Emergency Medicine, Department of Pediatrics, University of Cincinnati School of Medicine, Cincinnati, OH
[4]The George Washington School of Medicine and Health Sciences, Washington, DC
[5]Duke University School of Medicine, Durham, NC
[6]Department of Pediatric Emergency and Critical Care Medicine, Tokyo Metropolitan Children's Medical Center, Tokyo, Japan
[7]Division of Emergency Medicine, Department of Pediatrics, The George Washington School of Medicine and Health Sciences, Washington, DC

Corresponding author: Aaron Donoghue, MD, MSCE
Division of Critical Care Medicine
Children's Hospital of Philadelphia
34th Street and Civic Center Boulevard
Philadelphia, PA 19104
215-590-1289
donoghue@email.chop.edu

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ABSTRACT

Objectives: To describe chest compression(CC) quality by individual providers in two pediatric emergency departments (EDs) using video review and compression monitor output during pediatric cardiac arrests.

Methods: Prospective observational study. Patients <18 yo receiving CC for > 1 minute were eligible. Data was collected from video review and CC monitor device in a synchronized fashion and reported in 'segments' by individual providers. Univariate comparison by age (<1 yo, 1-8 yo, >8 yo) was performed by chi-square testing for dichotomous variables ('high-quality' CPR) and nonparametric testing for continuous variables (CC rate and depth). Univariate comparison of ventilation rate (V) was made between segments with an advanced airway versus without.

Results: 524 segments had data available; 42/524 (8%) met criteria for 'high-quality CC'. Patients >8 yo had more segments meeting criteria (18% vs. 2% and 0.5%; $p<0.001$). Segments compliant for rate were less frequent in <1 yo (17% vs. 24% vs. 27%; $p=0.03$). Segments compliant for depth were less frequent in <1 year olds and 1-8 year olds (5% and 9% vs. 20%, $p<0.001$.) Mean V for segments with an advanced airway was higher than with a natural airway (24 ± 18 vs. 14 ± 10 bpm, $p < 0.001$). Hyperventilation was more prevalent in CPR segments with an advanced airway (66% vs. 32%, $p < 0.001$).

Conclusions: CC depth is rarely guideline compliant in infants. Hyperventilation is more prevalent during CPR periods with an advanced airway in place. Measuring individual provider CPR quality is feasible, allowing future studies to evaluate the impact of CPR training.

BACKGROUND

More than 16000 children suffer cardiac arrest each year in the United States. High quality cardiopulmonary resuscitation (CPR) remains the cornerstone of therapy for cardiac arrest, and maintaining competency in CPR is a requirement for most pediatric healthcare personnel. Despite long-standing recommendations from the American Heart Association (AHA) on CPR quality, studies continue to show that CPR is frequently performed in a manner inconsistent with guidelines.[1,2] In pediatrics, the low incidence of cardiac arrest events raises a particular challenge for skill maintenance; studies have shown that the average provider in an emergency department (ED) performs chest compressions on children for only a few minutes per year.[3] There continues to be a need to optimize training in CPR to achieve durable skill acquisition and maintenance even in experienced pediatric healthcare providers.

Studies assessing pediatric CPR quality during actual patient events have been published using differing methods. Devices applied to a patient in cardiac arrest using pressure sensor, accelerometer, and transthoracic impedance can analyze individual chest compressions for depth, rate, and release. Multiple published studies in pediatric CPR have reported data from these devices to summarize quality across entire CPR events.[2,4,5] The use of video review has been shown to be a useful adjunct in assessing performance during CPR, albeit with limitations in accurately assessing chest compression depth.[1,6] Video review in conjunction with CPR monitor devices can allow comprehensive assessment of CPR performance by individual providers.

Members of our group recently reported on the simultaneous use of video review and pressure/accelerometer devices to measure chest compression quality at the level of individual providers in a case series examining hand position during infant CPR.[7] For the present study, we sought to report CPR performance quality data at the level of individual providers across a collaborative of pediatric EDs using video recording in their resuscitation areas. We hypothesized that measuring CPR performance by individual providers using a combination of video review and chest compression quality device measurement would be feasible, and that CPR would be provided to children in the ED with similar inconsistencies with published guidelines as has been demonstrated in other studies.

METHODS

Design and Setting

The Videography In Pediatric Emergency Resuscitation (VIPER) Collaborative is a multihospital research group of pediatric hospitals where video recording is used for quality assurance in the ED resuscitation area. This was an observational study conducted in two VIPER sites from September 2016 to March 2019. At each site, resuscitative care in the ED is video recorded as part of a intradivisional continuous quality assurance program. Patient/parent consent is obtained at the time of consent for treatment. Videorecording is done using multiple synchronized camera views plus a view of the patient monitor. Videos are reviewed and de-identified data is collected on common resuscitative procedures, including CPR. Following data collection, videos are deleted and are not part of the patient medical record. Figure 1 shows the configuration of the video systems used by the study centers (LiveCapture, BLine Medical, Washington, DC, USA; Ocularis OnSSI, Qognify Inc., Pearl River, NY) The study was approved by the Institutional Review Board of the Children's Hospital of Philadelphia.

The creation and testing of the VIPER database has been reported elsewhere.[8] Briefly, the database was created by the investigators through an iterative process using video recorded simulations as a source of test data. Duplicate review of CPR events by multiple investigators yielded very high interrater agreement with k > 0.8 for all dichotomous data fields and ICC >0.96 for continuous (time-based) data fields.

Subjects

All events where a patient received chest compressions (CCs) for $\geq$ 1 minute were eligible for inclusion. Events where a CC monitor device was not used, or where videorecording did not occur, were excluded. Data collected on patients included age, initial rhythm, out-of-hospital versus in-hospital cardiac arrest, event duration, and outcomes according to Utstein definitions that could be determined from video, i.e., return of spontaneous circulation (ROSC) and survival to hospital admission. Event duration was defined as the time from the first CC was performed by an ED provider to when ROSC was achieved, when the patient was cannulated for ECMO (or transferred out of the ED to the operating room for ECMO cannulation), or when the resuscitation was terminated and the patient was declared dead.

Data *c*ollection: Video review

CCs were analyzed by 'compressor segment', defined as the period of time where a single provider performed CC (with or without interruptions) until another provider replaced them. CC rate was expressed as compressions per minute (cpm). Start and stop times for each compression segment were measured to the nearest second. Individuals performing CCs were categorized based on their training background (nurse, paramedic, physician, etc.).

Ventilations were measured during video review by direct observation of the provider who was using the bag valve mask device. A ventilation was counted if the video reviewer could determine that the bag-valve mask device was squeezed in order to deliver a tidal volume to the patient (either through a mask, endotracheal tube, or supraglottic device). Ventilations were counted separately and expressed as breaths per minute (bpm).

Data collection: Monitor device

CC rate and depth were measured by the CC monitor device (R-series®, ZOLL Medical, Chelmsford, MA, USA) with dual sensor electrode pads in anterior-posterior position. Code Review™ software (ZOLL Medical, Chelmsford, MA, USA) was used to extract and analyze CC data; using start and stop time points for each compressor segment, the software allows for the selection of identical time periods and summarization of CC parameters for those time periods (i.e. CPR performance by individual providers).

The monitor devices are equipped with graphic readouts that provide real time feedback to CPR providers for depth and rate. However, these feedback graphic capabilities are only calibrated to guidelines for adult patients and are not available during CPR of smaller children (< 10 kg). Additionally, the configuration of the resuscitation areas of the two enrolling centers does not permit a line-of-sight view of the feedback interface during active CPR; thus, the data collected on rate and depth in this study was not influenced by real-time feedback.

Outcomes and Measures

The main outcome was performance of high quality CPR per compressor segment (unit of analysis). Current AHA recommendations for CPR parameters for infants and children are summarized in Table 1.[9] Compression segments were classified as 'high-quality CPR' if the following criteria were met: 1) average compression rate 100-120 per minute, 2) average compression depth 1.5 – 2 inches in infants aged less than 1 year and 2 – 2.5 inches in children > or = to 1 year of age, and 3) average ventilation rate between 8 and 12 breaths per minute. Compression segments were classified as 'high-quality chest compressions' if the aforementioned parameters for depth and rate were met (ignoring ventilation rate). AHA recommendations for compression depth are dichotomized into infants less than 1 year and children 1 year or older.[9] For the purposes of the current study, we stratified patient age into three categories: less than 1 year, greater than 1 to less than 8 years, and greater than or equal to 8 years. This age stratification has been previously published in a multisite pediatric ICU study of outcomes from in-hospital cardiac arrest.[5]

Analysis

All data was summarized descriptively. For CC parameters, unadjusted univariate analysis was performed between age strata using chi-square analysis for categorical variables and nonparametric methods (Kruskal-Wallis) for continuous variables. For ventilation rates, unadjusted univariate analysis was performed between CPR segments with a natural airway and segments with an advanced airway using chi-square analysis. All statistics were performed using STATA version 12 (College Station, TX).

RESULTS

93 CPR events occurred across both sites during the study period; a total of 938 chest compression segments were analyzed. Data on CPR quality was available for 77/93 (83%) of patient events.

Seventeen of 93 (18%) events were traumatic cardiac arrests; the remainder were medical. Thirty-four events occurred in infants (< 1 year of age), 20 in children aged 1-8 years, and 23 in children aged > 8 years. 56/77 (73%) of events were out-of-hospital cardiac arrests with CPR continued on arrival to the ED. Utstein outcomes (up to survival to admission) for all events and stratified by age and location are shown in Figure 2.

The median CPR event duration was 837 sec (IQR 496 – 1391 sec). The median CPR event duration was not significantly different across age strata (<1 year: 825 sec; 1-8 year: 905 sec; >8 year: 823 sec), between medical vs. traumatic arrests (938 sec vs 1198 sec), or arrest location (IHCA 696 sec vs. OHCA 837 sec).

Among the 524/923 segments with CC quality data available, 42/524 (8%) met criteria for 'high-quality CC'. Patients aged >8 years had a significantly higher proportion of compression segments meeting these criteria (18% vs. 2% in <1 years and 0.5% in 1-8 years; $p<0.001$). Data on chest compression and ventilation quality was simultaneously available for 300/938 segments. Within this subset of segments, 20/300 (7%) met all criteria for 'high-quality

CPR' (CC plus ventilations). Patients >8 years of age had a significantly higher proportion of CPR segments meeting these criteria (13% vs. 4% in <1 year and 1% in 1-8 years; $p<0.001$).

CC rate and depth stratified by age are shown in Figure 3. CC rate was not significantly different between the three age strata. The proportion of compression segments that were guideline compliant for rate was significantly lower in the <1 year age category compared with 1-8 year olds and >8 year olds (17% vs. 24% vs. 27% respectively; $p=0.03$). The proportion of compression segments that were compliant with age-specific guidelines for depth were significantly lower in both <1 year olds and 1-8 year olds compared with >8 year olds (5% vs. 9% vs. 20% respectively, $p<0.001$. Scatterplots of CC quality (rate and depth measured by compressor segments) stratified by age category are shown in Figure 4.

Median segment duration across all events was significantly shorter in >8 year old patients compared with <1 year and 1-8 years (59 sec vs. 70 sec vs. 73 sec respectively; $p=0.006$). The proportion of compressor segments that exceeded the recommended 120 second duration was higher in the <1 year old group than 1-8 years and >8 years (30% vs. 21% vs. 25%; $p=0.03$).

Across all events, 6% of compression segments were performed by attending or fellow physicians; 23% by resident physicians; 23% by nurses; 34% by EMTs or paramedics; and 14% by other provider categories (respiratory therapists, patient care associates, or unclassified personnel). Provider category stratified by site is shown in Figure 5. There were no significant differences in proportions of compression segments meeting criteria for either 'high-quality chest compressions' or 'high-quality CPR' among provider groups.

Figure 6 displays ventilation rates stratified by patients with an advanced airway (endotracheal tube, tracheostomy, or supraglottic device) and those ventilated without an advanced airway (natural airway with bag valve mask device). The mean respiratory rate for CPR segments with an advanced airway was significantly higher than for segments with a natural airway (24 $\pm$ 18 bpm vs. 14 $\pm$ 10 bpm, $p < 0.001$). Hyperventilation outside of AHA guidelines (8-12 breaths per minute) was present in 32% of CPR segments with a natural airway compared with 66% of CPR segments with an advanced airway ($p < 0.001$).

Discussion

In the present study, we demonstrated that CPR quality in children in two academic EDs was suboptimal in the majority of patients; CPR quality in infants was suboptimal in nearly all patients. These findings are consistent with past studies of CPR performance across a variety of settings.[1,2,5] Using a novel approach to CPR analysis, where video review was combined with CC device measurement, we were able to report CPR performance metrics in actual patient care at the individual provider level. To our knowledge, this is the first multicenter study reporting individual provider-level performance of CPR during actual pediatric cardiac arrests.

The recommendations for CC rate and depth in pediatric BLS guidelines continue to suffer from a lack of published data and are largely extrapolated from adult guidelines. Niles et al recently published a descriptive summary of pediatric CC quality during IHCA across an international consortium of pediatric ICUs.[5] They found that only 10% of 60-second epochs of CPR met guidelines for depth, rate, and compression fraction; compliance with depth was particularly poor in younger children. Our data supports these findings, in particular that shallow compressions are much more prevalent in infants than in older children in our data set. Sutton et al recently published data from a multi-PICU consortium of pediatric IHCA events, finding that slower average compression rates (average of < 100 cpm), while observed in only 5% of CPR events, were associated with improved survival.[10] Our data shows average compression rates similar to the Sutton study, with slow compressions being infrequent and compressions that are 'too fast' being common, especially in infants. The association between specific CC parameters and survival in children is not yet well understood.

In our study, hyperventilation occurred more frequently during CPR with an advanced airway in place compared to CPR with a bag-valve mask device. Hyperventilation is common during pediatric IHCA[4]; members of our group have previously reported on a significant prevalence of hyperventilation during CPR in the PED.[1] Hyperventilation during CPR is theorized to be deleterious because of the reduction in central venous return caused by increased intrathoracic pressure.[11] Although physiology supports that hyperventilation should be avoided, studies in both animal and clinical models have not consistently shown an association between hyperventilation and patient outcomes.[12-14] Our data suggest not only that hyperventilation is very common, but that the presence of an advanced airway may facilitate hyperventilation during pediatric CPR, although we cannot draw any association with its influence on outcomes.

81% of compressor segments in our study were shorter than two minutes in duration, as recommended by current AHA PBLS guidelines. This recommendation is based on the observation that chest compression quality has been shown to deteriorate within minutes for individual providers in mannequin and human studies.[15,16] 28% of compressor segments were shorter than 60 seconds. Switching compressors more often than necessary may theoretically cause longer and/or more frequent interruptions in CPR and a decreased chest compression fraction. Frequent pauses in CPR have also been shown to impact chest compression quality; Sutton et al found that early chest compressions following a provider switch were shallower in depth and had greater leaning force.[17] This finding may represent an opportunity for improvement in team dynamics during CPR in the PED.

There were significant differences in the proportion of CCs done by different categories of providers between the two sites. 77% of all CCs at site 1 were done by nurses, paramedics, and emergency medical technicians; by contrast, 42% of all CCs at site 2 were done by physicians. The overall quality of CCs did not vary significantly between sites despite these differences. However, the variation in who performs CCs in the PED has implications for determining optimal methods of CPR training. Members of our group published a descriptive study over a one year period where all CPR events were video recorded; the absolute amount of time that any individual throughout the entire ED provider pool was performing CCs was calculated over the course of the year.[3] Only 30% of all ED providers did CCs at any time throughout the year. The median amount of time for an individual ED provider to perform CCs in one year was 3 minutes; the maximum time observed for any one provider was 20 minutes in one year. This scant experience with CC performance, even at tertiary centers, makes skill maintenance from routine clinical duties alone impossible. As novel educational strategies such as high-frequency low-dose CPR skills training become more common [18,19], it will be important to tailor those strategies to the appropriate groups of providers, which may vary from one institution to another.[18,19]

Our study adds to the growing literature on the use of video review as a tool for measuring care quality during resuscitation. In pediatric emergency medicine, studies have been published in the past decade examining the use of video review for assessing care provision during CPR, tracheal intubation, and the performance of the primary survey in trauma patients. [1,7,20-26] [1,7,19-25] [1,7,19-25] [1,7,19-25] [1,7,19-25] [1,7,19-25] [1,7,23-29] [1,7,21-27] Video review has been shown to be a more robust data source for specific elements related to tracheal intubation when compared with standard written resuscitation records;[27] we believe our data on CPR represents another area where video review provides information (e.g. provider identity, duration of compression by individuals) that is seldom reliably available from written records. Some of these preliminary studies have also led to publication of quality improvement reports demonstrating measurable improvement in care using video-based data as a needs assessment. For example, Kerrey et al demonstrated a 50% reduction in oxyhemoglobin desaturation during tracheal intubation following the implementation of a peri-procedural checklist based on initial findings from video review.[28]

We believe that our data collection methodology holds promise for longitudinally measuring the impact of education and quality improvement work on CPR performance in children, providing a direct link between training and performance at the level of individual providers. Next steps for this research will include the use of individual feedback and quality review to providers, correlating performance in real events with performance during training, and the eventual development of CPR skill training that can be adapted and contextualized to individual providers' needs. Additionally, we hope that video review will serve as a useful method for examining team-level logistics during cardiac arrest management, allowing focus on leadership, communication, choreography of actions, and systematic continuous quality improvement.[29]

Limitations

Our data was collected at two tertiary pediatric hospitals. The majority of pediatric CPR events in hospital EDs occur at non-tertiary centers. While the epidemiology of pediatric cardiac arrest is likely to be very similar between these two sites and other hospitals in the US, it remains possible that the generalizability of our findings to other centers is limited.

One of our most important findings was the high prevalence of hyperventilation during pediatric CPR, along with its association with the presence of an advanced airway. As previously described, counting ventilations from video consists of observing a provider squeezing the bag of a bag-valve-mask device and counting the frequency. We do not have the capability to measure airflow, tidal volume, or inflating pressure to determine whether visualized artificial breaths are in fact effective or not. Because a substantial amount of the CPR we analyzed was done with a natural airway, we did not have interpretable capnographic waveforms as a source of data on ventilation rate as has been reported in other studies.[30] Nonetheless, we believe that the rate of attempted assisted ventilations is a meaningful outcome in terms of whether a given provider is following guidelines or not.

Our study examined the performance of CPR in pediatric EDs. The overall survival of the cohort was poor, in keeping with most published studies of pediatric CPR in the ED. Most of our patients were OHCA patients, representing an epidemiologic group among cardiac arrest patients for whom outcomes have remained poor and improved negligibly over several decades. There are multiple examples of surrogate outcomes in literature on CPR quality such as ROSC and first defibrillation success; these studies provide evidence that optimized CPR performance has the potential to influence clinical outcomes, and that measuring CPR performance objectively is desirable. We believe video review is a feasible methodology for quantifying CPR performance and may yield a measureable process that can be studied prospectively as a metric of care delivery independent of clinical outcomes, with the eventual goal of improving pediatric CPR training on a large scale to improve survival from pediatric cardiac arrest.

Conclusions

Across a collaborative of PEDs using videorecording during resuscitative care, CPR in children was infrequently compliant with published guidelines. CCs were most commonly too shallow in infants with cardiac arrest. Hyperventilation was very common and significantly more frequent during CPR with an advanced airway in place. The simultaneous use of videorecording and CPR monitor devices allows the measurement of CPR quality at the level of individual providers, and future research should use similar methodology to evaluate the impact of novel methods of CPR skills training on individuals' chest compression quality during pediatric cardiac arrest.

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FIGURE LEGENDS

Figure 1: Screenshots from video review systems (circle in red corresponds to one view of bag valve mask device where ventilation rate could be determined)

Figure 2: Utstein outcomes

Figure 3: Chest compression rate and depth by age category

Figure 4: Scatterplots of chest compression rates and depth by age category

Figure 5: CPR provider categories at both sites

Figure 6: Ventilation rates (by airway category)

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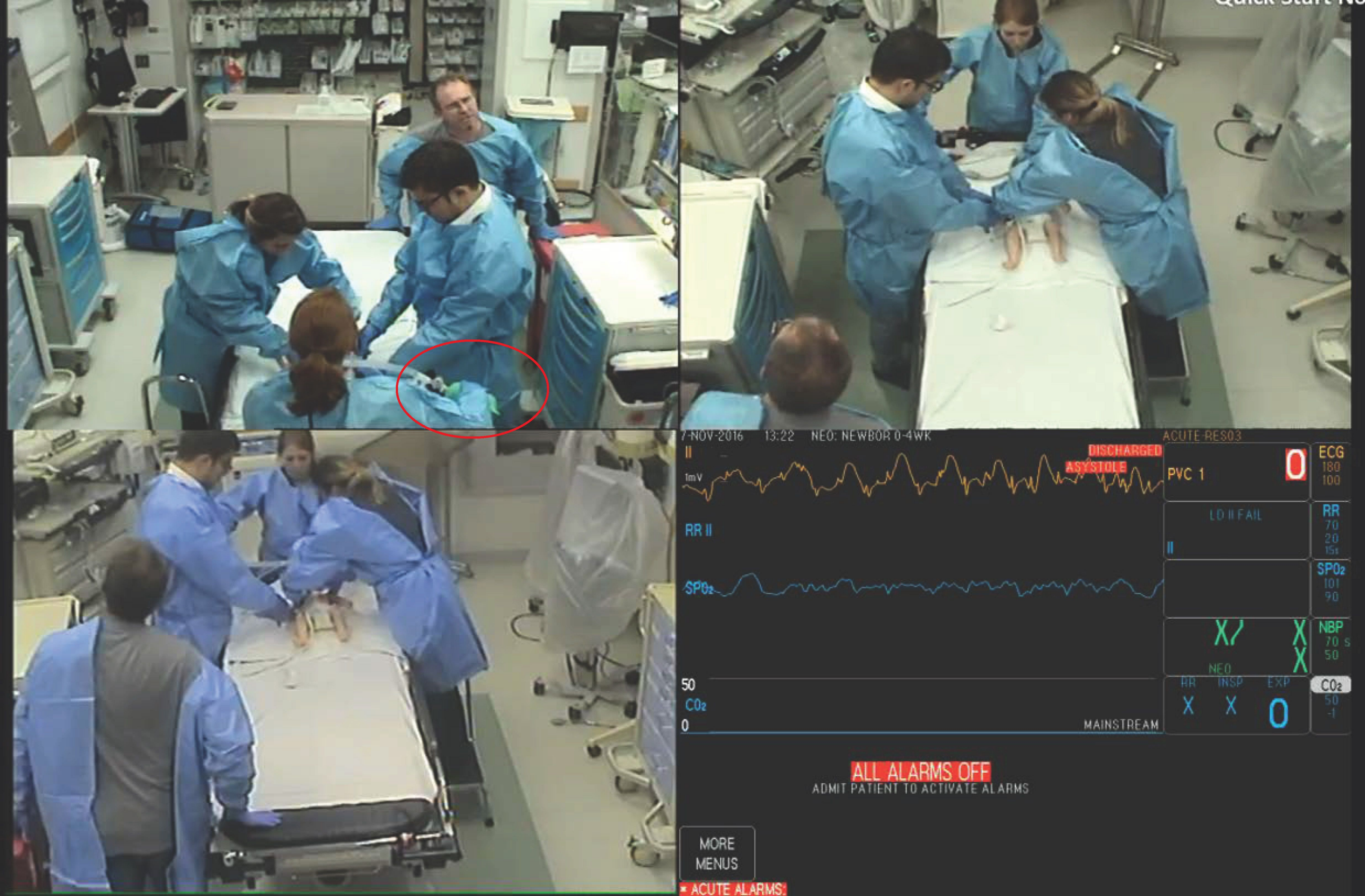
Table 1: AHA guidelines

Chest Compressions	Ventilation

• Rate: 100-120 per minute
• Depth:
  ○ Infants: 1.5 – 2.0 inches
  ○ Children: 2.0 – 2.5 inches
• Change compressor every 2 minutes
	• Compression ventilaton ratio 15:2
	• Intubated patients 10 bpm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ECG
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CO2
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ADMIT PATIENT TO ACTIVATE ALARMS
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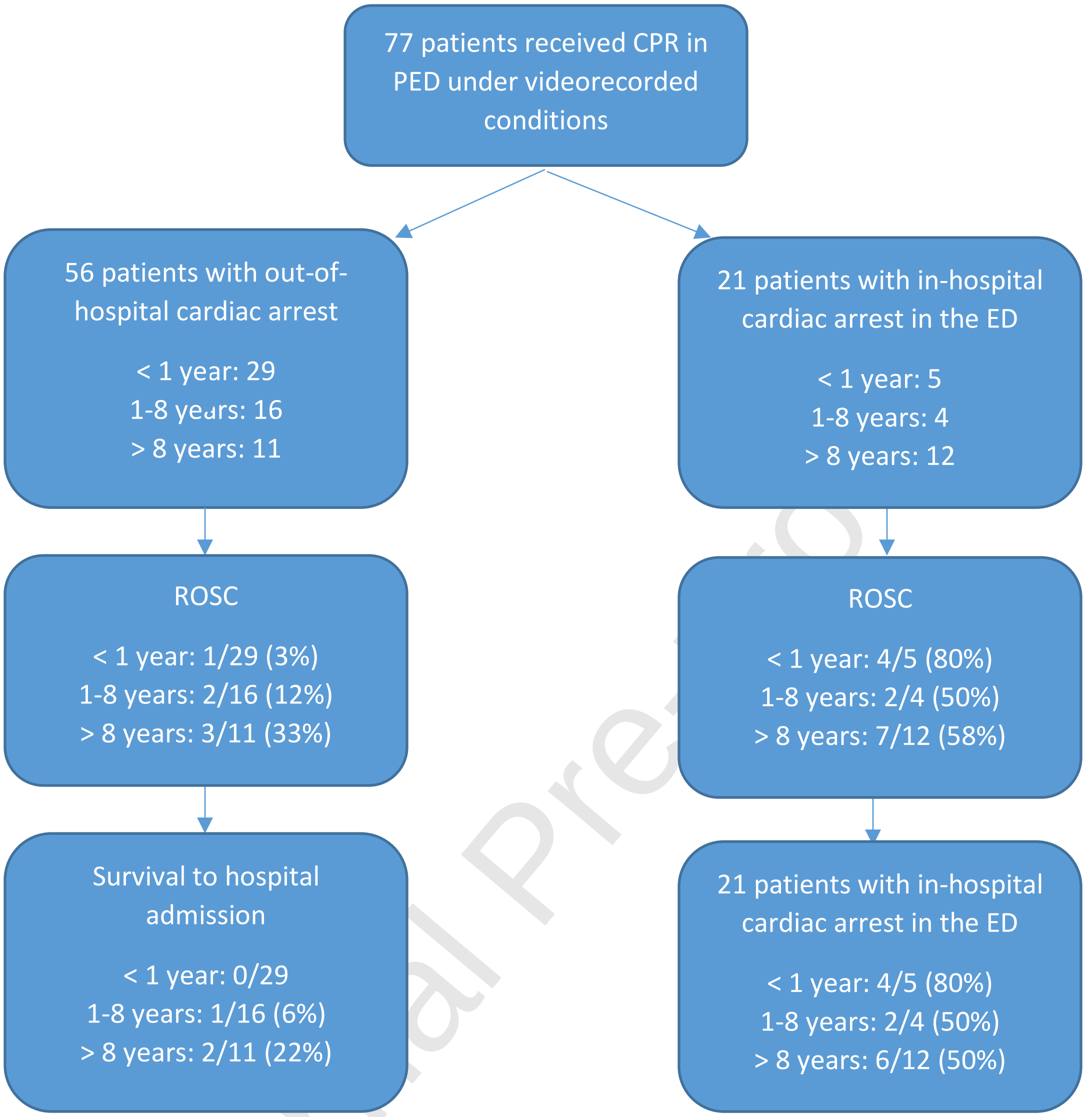
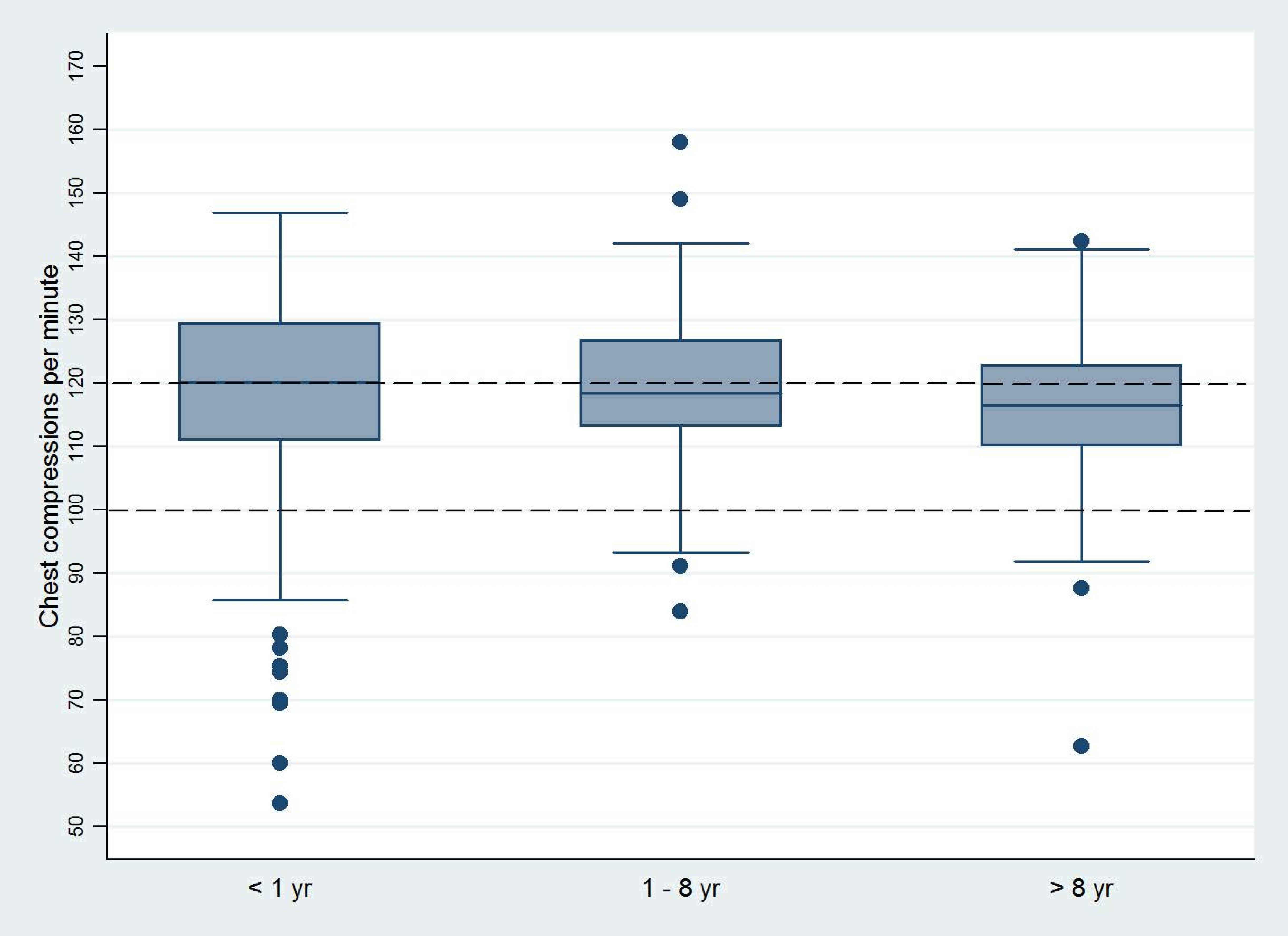
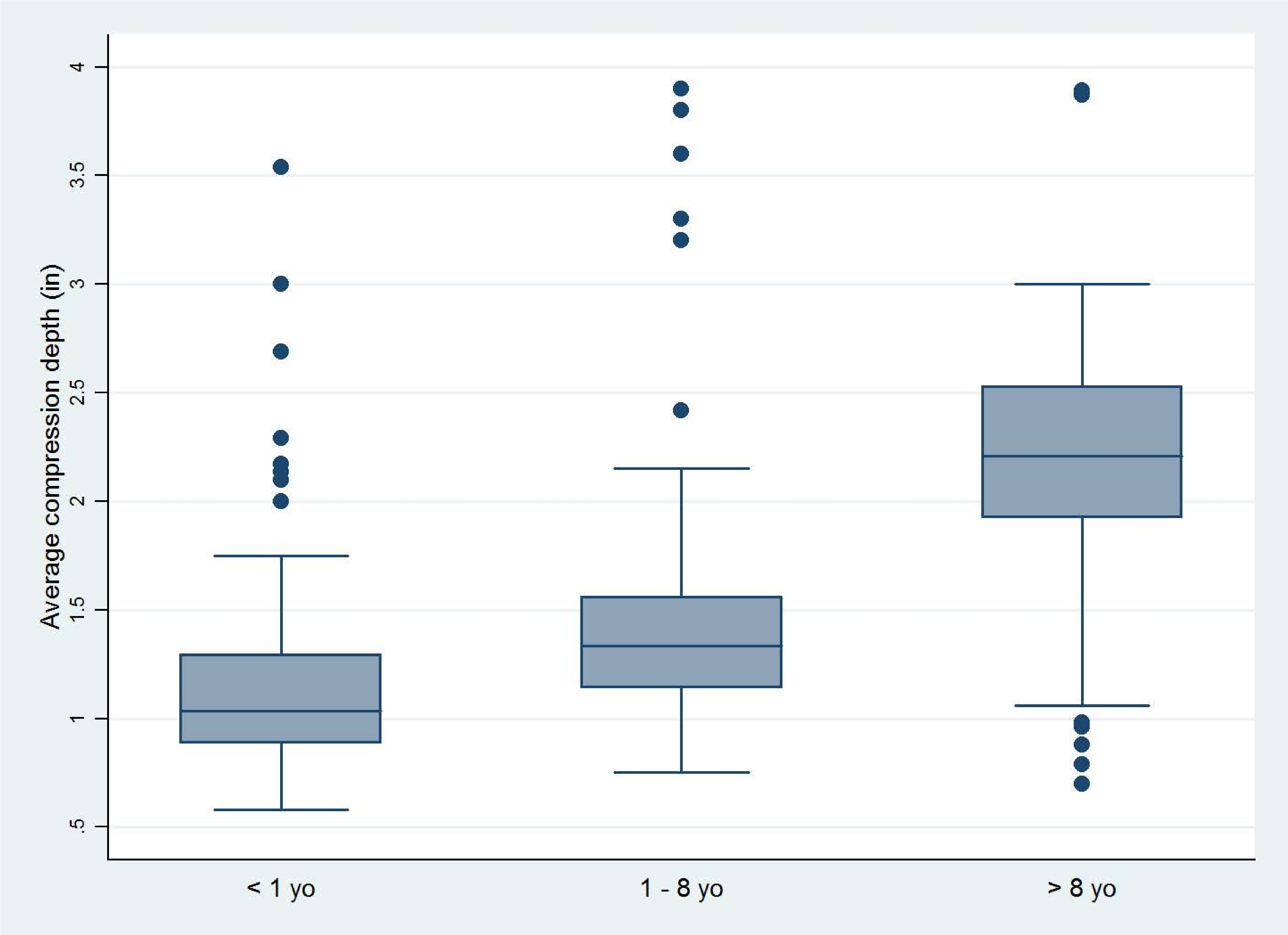
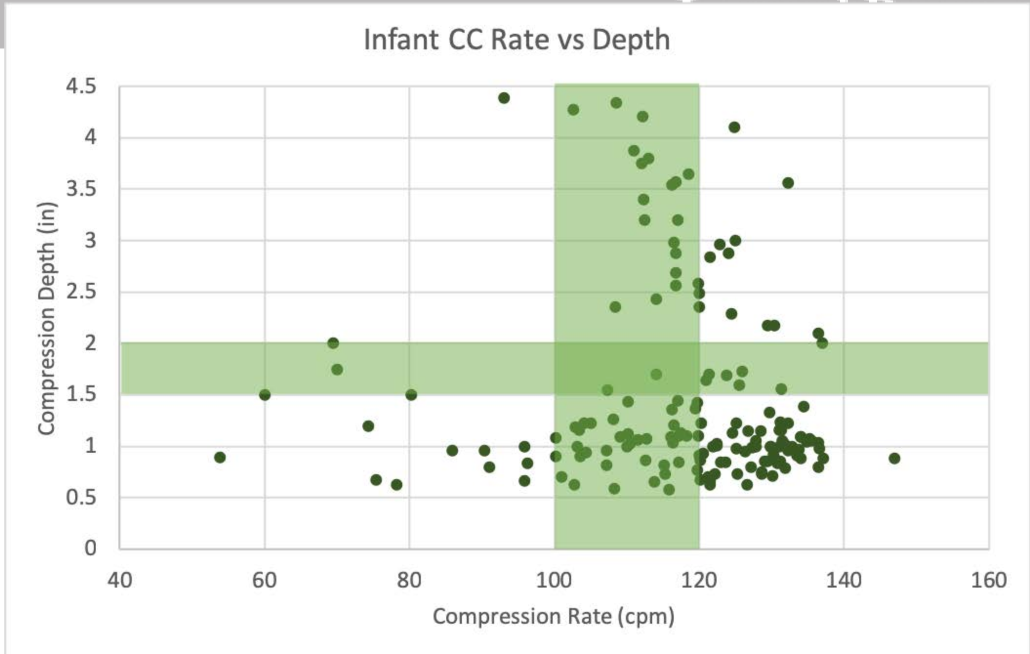

77 patients received CPR in PED under videorecorded conditions
56 patients with out-of-hospital cardiac arrest
< 1 year: 29
1-8 years: 16
> 8 years: 11
21 patients with in-hospital cardiac arrest in the ED
< 1 year: 5
1-8 years: 4
> 8 years: 12
ROSC
< 1 year: 1/29 (3%)
1-8 years: 2/16 (12%)
> 8 years: 3/11 (33%)
ROSC
< 1 year: 4/5 (80%)
1-8 years: 2/4 (50%)
> 8 years: 7/12 (58%)
Survival to hospital admission
< 1 year: 0/29
1-8 years: 1/16 (6%)
> 8 years: 2/11 (22%)
21 patients with in-hospital cardiac arrest in the ED
< 1 year: 4/5 (80%)
1-8 years: 2/4 (50%)
> 8 years: 6/12 (50%)

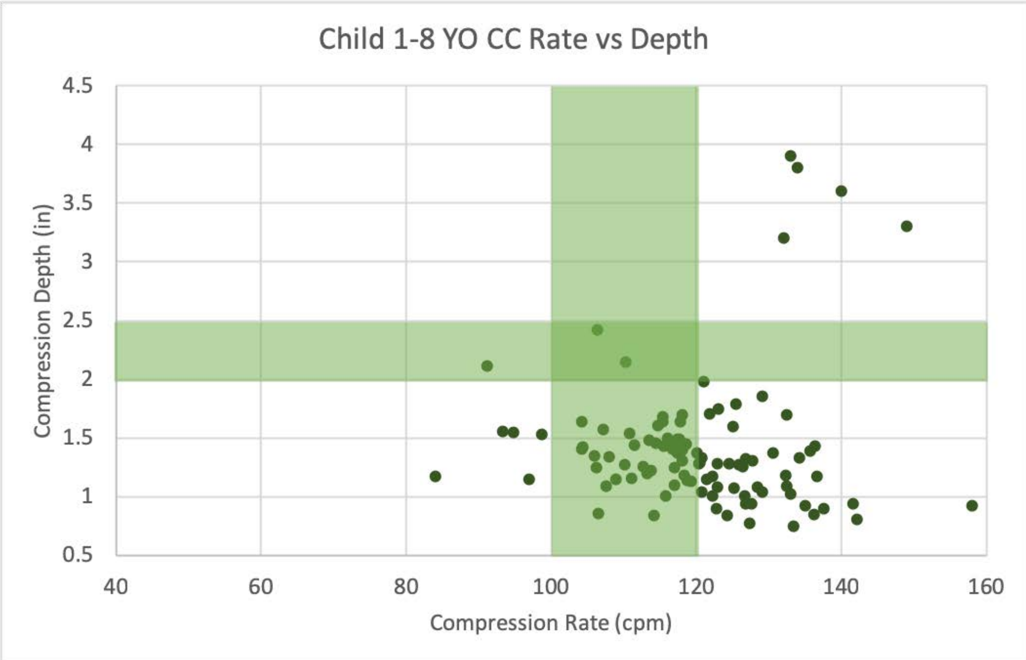


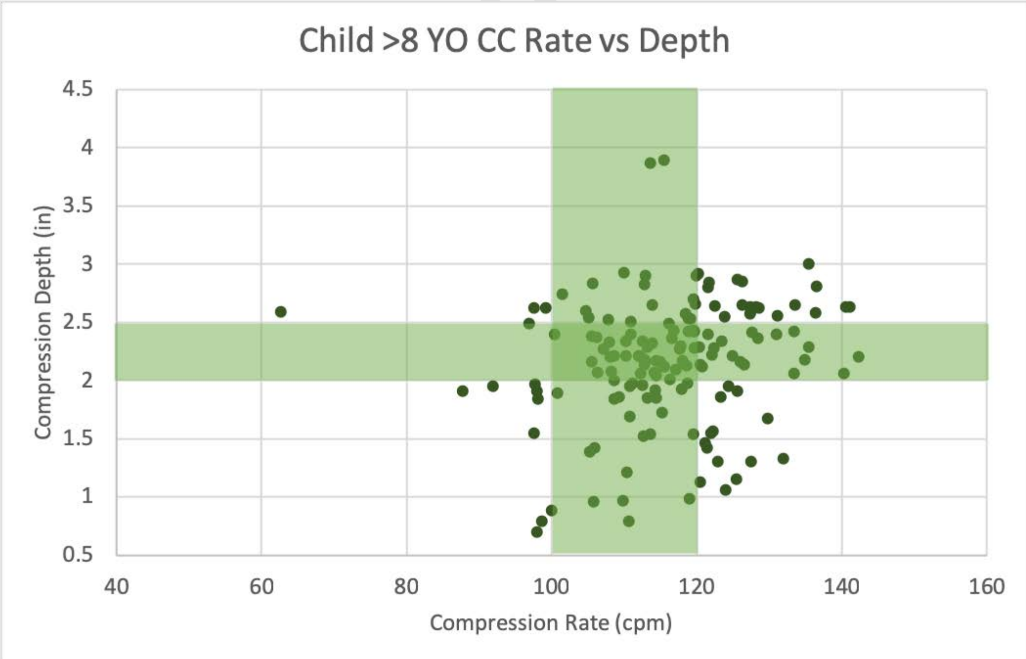
Chest compressions per minute
50
60
70
80
90
100
110
120
130
140
150
160
170
< 1 yr
1 - 8 yr
> 8 yr

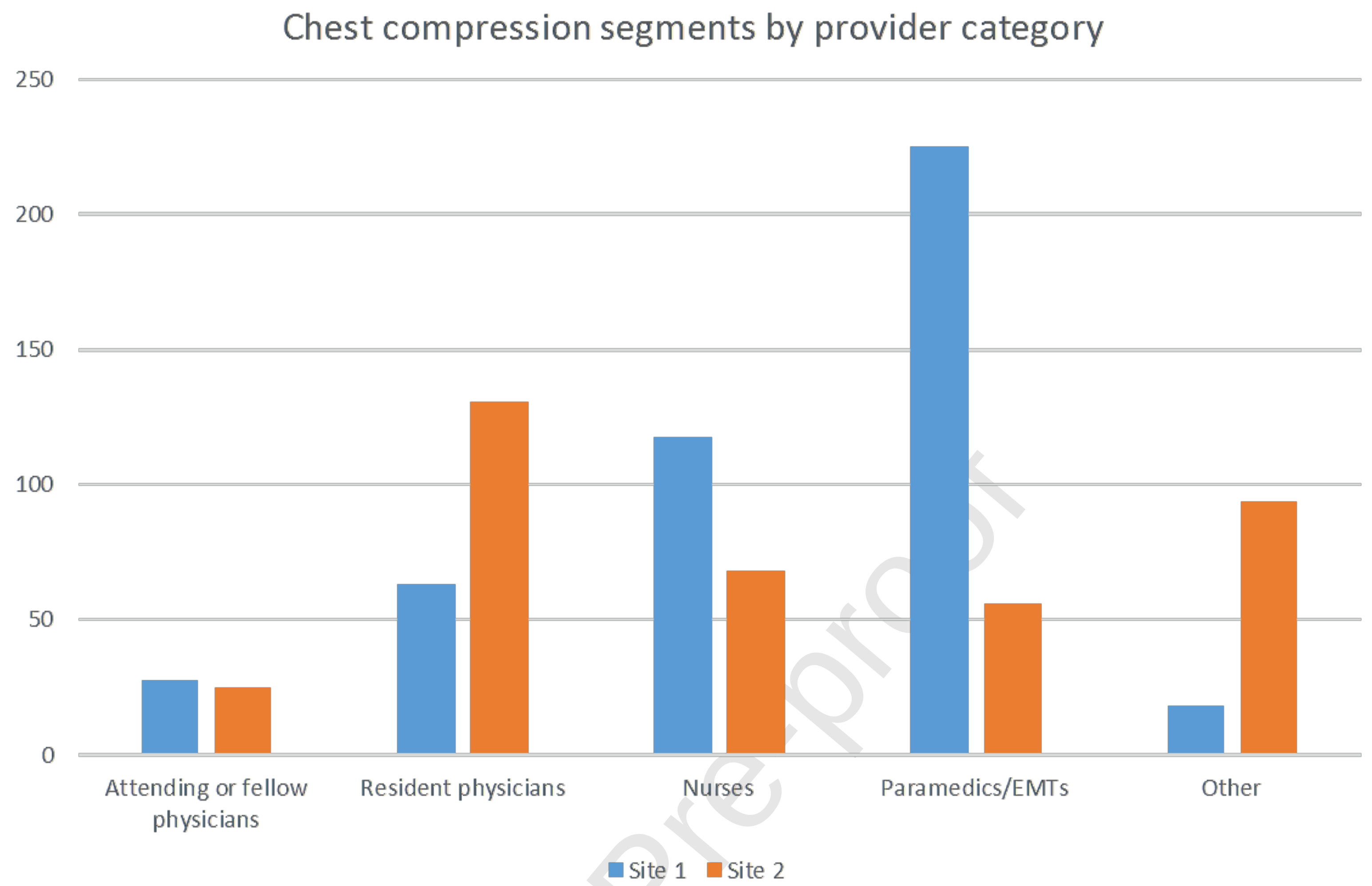


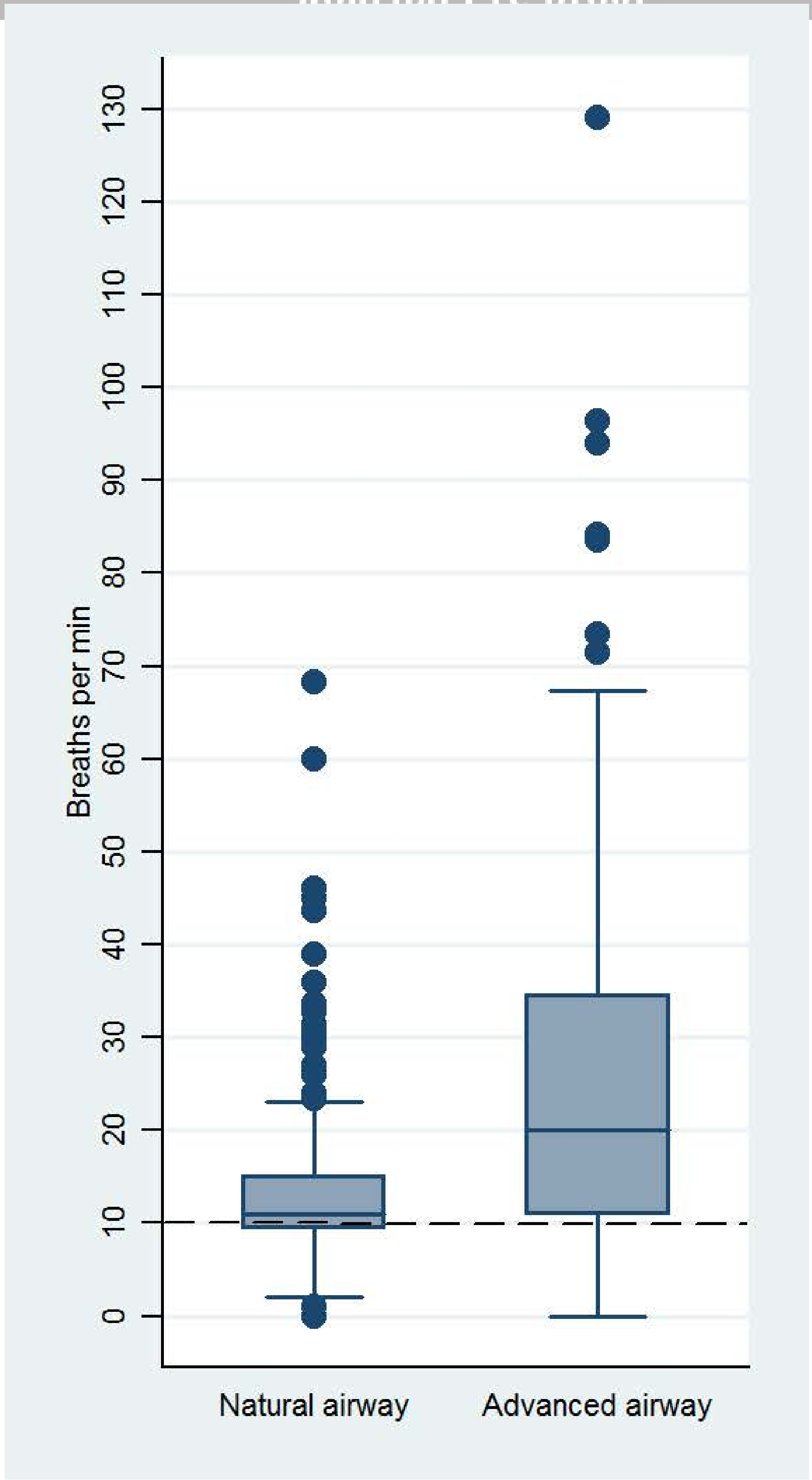
Average compression depth (in)
.5
1
1.5
2
2.5
3
3.5
4
< 1 yo
1 - 8 yo
> 8 yo


Infant CC Rate vs Depth
Compression Depth (in)
Compression Rate (cpm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
40
60
80
100
120
140
160


Child 1-8 YO CC Rate vs Depth
Compression Depth (in)
Compression Rate (cpm)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
40
60
80
100
120
140
160


Child >8 YO CC Rate vs Depth
Compression Depth (in)
Compression Rate (cpm)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
40
60
80
100
120
140
160


Chest compression segments by provider category
250
200
150
100
50
0
Attending or fellow physicians
Resident physicians
Nurses
Paramedics/EMTs
Other
Site 1
Site 2


Breaths per min
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Natural airway
Advanced airway