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Comparison of relative and actual chest compression depths during cardiac arrest in children, adolescents, and young adults*

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Abstract

Aim—Cardiopulmonary resuscitation (CPR) guidelines recommend specific chest compression (CC) target depths for children. We quantitatively describe *relative* anterior–posterior diameter (APD) depth, *actual* depth, and force of CCs during real CPR events in children.

Methods—CC depth and force were recorded during real CPR events in children 8 years using FDA-approved CC sensor. Patient chest APD was measured at conclusion of each CPR event. CC data was stratified and analyzed according to age (pre-puberty, 8–14 years; post-puberty, 15+ years). Relative (% APD) and actual CC depth, corrected for mattress deflection, were assessed and compared with American Heart Association (AHA) 2005 and 2010 pediatric CPR guidelines.

Results—35 events in 32 subjects included 16,158 CCs for data analysis: 16 pre-puberty (CCs = 7484, age 11.9 ± 2 years, APD 164.6 ± 25.1 mm); 19 post-puberty (CCs = 8674, age 18.0 ± 2.7 years, APD 196.5 ± 30.4 mm). After correction for mattress deflection, 92% of CC delivered to pre-puberty were $<1/3$ relative APD and 60% of CC were <38 mm actual depth. Mean actual CC

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Conflict of interest statement

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depth (36.2 ± 9.6 mm vs. 36.8 ± 9.9 mm, $p = 0.64$), mean relative APD ($22.5\% \pm 7.0\%$ vs. $19.5 \pm 6.7\%$, $p = 0.13$), and mean CC force (30.7 ± 7.6 kg vs. 33.6 ± 9.4 kg, $p = 0.07$) were not significantly less in pre-puberty vs. post-puberty.

Conclusions—During in-hospital cardiac arrest of children ≥ 8 years, CCs delivered by resuscitation teams were frequently $<1/3$ relative APD and <38 mm actual depth after mattress deflection correction, below pediatric and adult target guidelines. Mean CC actual depth and force were not significantly different in pre-puberty and post-puberty. Additional investigation to determine depth of CCs to optimize hemodynamics and outcomes is needed to inform future CPR guidelines.

Keywords

Cardiopulmonary resuscitation; Chest compression; CPR; Cardiac arrest; Children; Pediatric

1. Introduction

Quality of cardiopulmonary resuscitation (CPR) is critical for survival and good neurological outcome following cardiac arrest.^{1,2} However, translation of evidence-based, consensus-derived international consensus on science and treatment recommendations³ for CPR to the bedside has been difficult to achieve.^{4,5} This is particularly important because greater compliance with CPR guidelines is associated with better outcomes.^{6–8}

In 2010 the American Heart Association (AHA) updated its recommended guidelines to facilitate training and implementation of high-quality CPR, specifically, adequately deep CCs. Importantly, the recommended depth of CC for adults and pediatrics is now deeper. For adults, 2005 CC depth targets increased from “ $1\frac{1}{2}$ –2 in. (38–51 mm)” to a target in 2010 of “at least 2 in. (5 cm).”⁹ For children >1 year of age, the CC depth targets in 2005 changed from “push with sufficient force to depress the chest approximately one third to one half the anterior–posterior diameter of the chest” to “push with sufficient force to depress at least one third the anterior–posterior diameter of the chest or approximately 2 in. (5 cm).”⁹ Similarly, the European Resuscitation Council (ERC) and the International Liaison Committee on Resuscitation (ILCOR) recommended pediatric CC depth targets of “approximately one third (33%) the anterior–posterior diameter of the chest.”¹⁰

Interestingly, the 2005 American Heart Association Guidelines for pediatric basic life support were intended for children “from about 1 year of age to the onset of adolescence or puberty (about 12–14 years of age) as defined by the presence of secondary sex characteristics” whereas adult basic life support guidelines were intended for adolescents post-puberty. Because pre-pubertal children are smaller than post-pubertal adolescents and because age cut-offs are often difficult for rescuers to appreciate, the 2010 American Heart Association Guidelines further specified the pediatric age to “puberty ... defined as breast development in females and the presence of axillary hair in males.”¹¹

The pediatric basic life support CC depth guidelines for children from 1 year old to puberty are based upon consensus and, to a lesser extent, animal and theoretical radiographic imaging studies, not on actual human CPR data.¹² Therefore, we evaluated CPR quality data during actual CPR guided by informed and experienced pediatric ICU and ED providers at a large children’s hospital. The primary objective of this study was to determine CC depth relative to anterior–posterior diameter (% APD) and actual compression depth delivered to real children in a tertiary care pediatric intensive care unit (PICU) and emergency department (ED) guided by resuscitation leader attending physician and staff focused on high quality CPR, and compare the current practice to existing CC depth guidelines. A secondary objective was to compare the relative % APD CC depth achieved for pre-pubertal

children vs. post-pubertal adolescents, and relate these depths to those previously reported in adults. The final objective was to describe the depth of corrected CC using the 2005 vs. new 2010 AHA guideline CC targets of $\geq 1/3$ APD or ≥ 50 mm using APD measurements of real children who received CPR in the PICU and ED.

2. Methods

2.1. Study design

This prospective observational study was approved by the Institutional Review Board at The Children's Hospital of Philadelphia. Data collection procedures were completed between October 2006 and December 2009 in compliance with the guidelines of the Health Insurance and Portability and Accountability Act to ensure subject confidentiality. Written informed consent for cardiac arrest subjects was waived since all data collected were de-identified. Written informed consent was obtained from all health care providers who provided chest compressions during the resuscitations.

2.2. Equipment and training

Data were collected using an FDA-approved (ages 8+ years old) commercial monitor/defibrillator system (Heartstart MRx/Q-CPR, Philips Healthcare, Andover, MA, USA) equipped with a CC force and deflection sensor (FDS) on patients 8 years and older. The monitor/defibrillator records and provides audiovisual corrective and directive feedback if quality CC guideline targets (rate $90\text{--}120\text{ min}^{-1}$, depth $38\text{--}51\text{ mm}$, residual force $<2.5\text{ kg}$, $<15\text{ s}$ pause between CCs) are not reached. Data are stored internally in the defibrillator for later review and analysis. Data included chest compression rate (average rate/min and actual # delivered/min), depth (mm), force (kg), and type and time of audiovisual feedback prompts.

More than 90% of pediatric health care providers (physicians, nurses, respiratory therapists, and emergency medical technicians) in the Pediatric Intensive Care Unit (PICU) and Emergency Department (ED) received extensive defibrillator and FDS training prior to implementation of the Q-CPR monitor/defibrillators and subject enrollment. This rigorous training consisted of: (1) completing a checklist of competencies, (2) performing chest compressions to AHA 2005 Basic Life Support guideline standards using the FDS on an adult manikin (Resusci Anne, Laerdal Medical AS, Stavanger, Norway), and (3) receiving frequent, periodic, brief retraining sessions ("Rolling Refreshers") at the point of care.¹³ Resuscitation teams consisted of team leaders which were board-certified pediatric emergency and critical care attending and fellow physicians. The CC depth was guided by the code leader's assessment of appropriate CC depth for the patient based upon feedback from clinical signs, multiple monitors and devices as available for each patient. The resuscitation team was trained so that the CPR audiovisual corrective and directive feedback monitor/defibrillator was an adjunct to the clinical team resuscitation leader's directions.

2.3. CPR event forensic engineering reconstruction

Patient AP chest depth was obtained at the conclusion of the resuscitation event while the subject was supine on the backboard. One end of a tape measure was placed on the surface immediately lateral to the subject's torso. The maximum height above the surface of the anterior aspect of the chest, halfway between the xyphoid and manubrium, was measured by a member of the research team specifically trained and experienced in this procedure. Because the FDS technology is based on measuring acceleration, the depth calculated by the FDS represents the total movement of the FDS itself, and not only the deflection of the chest.^{14,15} When the patient is on a mattress, the depth reported for real-time feedback is consequently the sum of both the mattress and patient chest deflection. As a result, CC depth

was corrected for residual leaning force/depth and mattress deflection utilizing CPR event forensic engineering reconstruction, as previously described.¹⁶ To estimate the actual CC depth of the patient (corrected depth), the mattress deflection results of the forensic engineering reconstruction was subtracted from the measured total compression depth (uncorrected depth) from the actual event. This corrected depth was also used for the calculation of the relative %APD CC depth.

2.4. Definition of pediatric/child

For the purpose of stratification and analysis, we prospectively defined pre-puberty children as 8–14 years old, and post-puberty adolescents as 15 years old, as per AHA Guidelines.^{11,17}

2.5. Data analysis

A Microsoft Windows based software program, Q-CPR Review (version 2.1.0.0, Laerdal Medical AS, Stavanger, Norway), was used for initial examination and analysis of CC data. Corrected CC depth was calculated based on mattress reconstruction results. Due to the first CCs typically being inconsistent in quality, the initial 5 chest compressions of each event were removed from analysis, and the subsequent CCs, up to 500 CCs per event, were analyzed. Absolute corrected CC depth and relative CC depth (total corrected CC depth/ anterior–posterior chest diameter) in % APD were calculated and compared with AHA 2005 (in effect at the time CCs were delivered) and newly revised 2010 pediatric CPR guidelines. Descriptive statistics (mean $\pm$ SD) were reported, and two-level analyses with events as clusters, nested with multiple compressions were performed. This hierarchical model was developed with a random effect for intercept and a fixed effect within clusters. This analysis was performed using Stata version 11 (Stata Corp, College Station, TX, USA).

3. Results

There were a total of 50 pediatric cardiac arrest events requiring CCs utilizing the MRx/Q-CPR defibrillator and FDS. Fifteen events were excluded due to incomplete data (FDS CC data not stored, 1; mattress reconstruction not able to be completed, 3; no APD data, 11). The remaining 35 events in 32 subjects included 16,158 chest compressions for data analysis; 16 subjects in the pre-puberty cohort (8–14 years old) received 7484 CCs and 19 subjects in the post-puberty-adult cohort (15+ years old) received 8674 CCs. All subjects were on a backboard during their resuscitation event.

Event demographic data are presented in Table 1. Mean subject age for the pre-puberty group was 11.9 ± 2.0 years, weight 42.5 ± 7.9 kg, and the mean APD was 164.6 ± 25.1 mm. Fifty percent (8/16) were female and the majority of the pre-pubertal CPR events occurred in the Emergency Department (ED) (56%, 9/16). Mean subject age for the post-puberty-adult group was 18.0 ± 2.7 years, weight 50.2 ± 13.6 kg, and mean APD was 196.5 ± 30.4 mm. Fifty-three percent (10/19) were female and the majority of the post-pubertal CPR events occurred in the PICU (74%, 14/19).

3.1. All chest compression events

Mean corrected CC depth relative to APD for all events was $20.9\% \pm 7.0\%$ with a mean corrected CC depth of 36.5 ± 9.8 mm, and a mean CC force 32.3 ± 8.7 kg. For all events, 63% (22/35) had a mean corrected CC depth ≥ 38 mm and 9.6% (1/35) had a corrected depth of ≥ 50 mm.

Overall, 23 of 35 (66%) of events had an average event corrected CC depth <38 mm. Comparison of ROSC between events that did not achieve an average depth of 38 mm vs.

those that did revealed no statistically significant difference between the groups (<38 mm: 6/23 (26%); 38 mm: 3/12 (25%), $p = 1.0$). Similarly, there was also no difference in survival to hospital discharge between these 2 groups (<38 mm: 1/23 (4%); 38 mm: 1/12 (8%), $p = 1.0$). We were unable to associate survival with depth using >1/3 APD as the measure of compliance due to no event achieving an average event depth exceeding 1/3 APD.

3.2. Chest compressions stratified by age

Of the pre-puberty events, 37.5% (6/16), and 21% (4/19) of the post-puberty events had CCs that reached 1/3 APD. However 81.3% (13/16) of the pre-puberty events and 95% (18/19) of the post-puberty events had CCs that reached 38 mm (Table 2). The mean CC depth relative to APD in the pre-puberty group was $22.5\% \pm 7.0\%$, with a mean corrected CC depth of 36.2 ± 9.6 mm. The post-puberty group's mean CC depth relative to APD, mean corrected CC depth, and mean CC force was not significantly different from the pre-puberty group (Table 3).

3.3. Actual chest compression depth vs. recommended depth

Fig. 1 displays the distribution of corrected CC depths relative to APD among children in the pre-puberty group. The pre-puberty group had more CCs >1/3 APD than the post-puberty group (7.8% vs. 5.2%, $p = 0.002$) while none of the compressions reached 1/2 APD in any of the subjects. When analyzed and compared to AHA 2005 (in effect at time of data collection) and new 2010 guidelines, there was no significant difference between the groups for both the 38 mm (40% vs. 41%, $p = 0.49$) and 50 mm measurement (9% vs. 10%, $p = 0.53$) (Table 4). However, significantly more CCs reached 1/3 APD than in the pre-puberty than in the post-puberty group (7.8% vs. 5.2%, $p = 0.002$).

Using the 2005 CC adult guideline targets, a 38 mm CC depth would reach a greater APD in the pre-puberty than in the post-puberty subjects ($23.6\% \pm 3.5\%$ vs. $19.8\% \pm 3.2\%$). Similarly, a greater APD would be reached in the pre-puberty vs. the post-puberty subjects using a 2010 recommended 50 mm CC depth target ($31.0\% \pm 4.5\%$ vs. $26.0\% \pm 4.3\%$) (Table 5). When we plot the 2005 adult (< 38 mm) and 2010 pediatric and adult (< 50 mm) CC minimum guideline targets on the distribution of relative APD of 8–14 year-old pre-puberty subjects (Fig. 2a: 1/3 APD; Fig. 2b: 1/2 APD), there is a greater likelihood of reaching 1/3 APD with a 50 mm CC vs. a 38 mm CC.

4. Discussion

This study systematically reports the relative and absolute chest compression depths delivered to older children, adolescent and young adult patients during actual CPR guided by pediatric ICU and ED providers. After compensating for mattress compression, 92.2% of CCs delivered to in-hospital cardiac arrest victims 8–14 years were less than 1/3 AP chest depth (the minimum pediatric CC recommendation at the time of data collection). In addition, 59.8% of the pre-puberty events had mean corrected CC depth of less than 38 mm (the minimum adult CC recommendation at the time of data collection).

In a study previously published by our research group, we reported the quantitative assessment of chest compression quality including a small number of the same events from this study. However, a number of important differences exist between the 2009 report and this study. Specifically, a completely different analysis approach was taken for this study in order to report *mattress compensated depth*, percent AP compression depth and the 2010 (not available in 2009) AHA Guidelines. In addition, the 2009 report analyzed and divided the data into 30 sec segments of actual measured chest compression *without mattress compensation*. In this report, we determined average corrected compression depth *per*

patient for process of care outcomes (compliance with AHA Guidelines) against both the 2005 and 2010 AHA Guidelines.

Unlike evidence-based CC depth recommendations for adults, specific evidence for target depth of CC in children is lacking; thus, therapeutic targets for pediatric CCs have been based on expert consensus. As an example, a CC depth relative to the anterior-posterior chest depth (% APD), rather than an absolute depth, was previously recommended for children in order to encourage deeper CCs. This recommendation, however, was not based on real pediatric CPR, hemodynamic, or outcome data. In 2010, the AHA guidelines, ERC guidelines, and ILCOR consensus on science with treatment recommendations for pediatrics were updated, in order to encourage rescuers to provide adequately deep CCs. Conversely, these guidelines were developed from knowledge extrapolated from adult CC data, animal models, CT measurements of chest depth, and descriptive data of reported continued delivery of shallow CCs by rescuers.^{4,5,8,12,18} After utilizing a mattress correction analysis,¹⁶ we calculated relative and absolute CC depth and compared our findings to previous (2005) and current (2010) adult and pediatric CC depth recommendations. From our results, a CC depth of 38–51 mm corresponds to 22–29% APD in these patients 8–22 years of age receiving in-hospital CPR. However, when stratified by age, 38–51 mm corresponds to 24–32% APD for these 8–14 year olds, and 20–27% APD for these subjects 15 years or above. Pickard et al.¹⁹ found that the external compression depth target for adults, 38–51 mm, corresponded to ~6–20% APD for their cohort of male adults and 17–21% for their cohort of female adults. It would appear from these data that an increase in absolute CC depth targets may be warranted in order to achieve a greater APD percentage which may elicit improved hemodynamics.^{5,18,20–23}

Several studies of in-hospital and out-of-hospital CPR support current AHA emphasis on adequately deep CCs, by linking quality of CPR measures with patient survival outcomes.^{4,5,7,8} In an attempt to improve adherence to expert guideline recommendations, quantitative CPR quality monitoring systems have been developed and utilized during adult resuscitation attempts. Real-time audiovisual directive and corrective CPR feedback can improve adherence to guidelines and resuscitation outcomes.²⁰ These systems utilize force transducer and accelerometer technology and are able to determine chest deflection (mm) during a given CC. Extension of this real-time audiovisual CPR feedback technology, which relies on absolute depth measurements, to provide feedback to younger subjects requires determination of reasonable target depths for those children, and may require compensation for soft hospital beds. In our study population of 8–14 year olds, using 2005 adult guidelines of 38–51 mm, healthcare providers only delivered minimally guideline compliant CC depth 59% of the time, equivalent to $22 \pm 4\%$ APD. Looking toward the new 2010 guidelines in our pre-pubertal population (8–14 years), a CC of 50 mm would compress 38% (6/16) of the subject chests to $>1/3$ APD but would not reach $1/2$ APD in any of the subjects. A 50 mm CC would compress to a mean 31% APD. Consequently, the use of a constant CC depth target of 50 mm may not be harmful for this pediatric pre-pubescent (8–14 year old) population, however this study does not directly address the harm/safety of this practice.

Greater compliance with CPR guidelines has previously been associated with better outcomes in other settings.^{6–8} This study was not intended, nor powered, to associate depth of chest compression with outcome. In this selected population, average event corrected CC depth <38 mm vs. 38 mm was not statistically associated with a difference in ROSC or survival to hospital discharge, but the power to detect a difference was very low ($p = 1.0$). Additional multi-center investigation with appropriate power should be completed to properly correlate the significance of CC depth with ROSC and mortality.

Studies of adult CPR demonstrate that even with real-time audiovisual directive and corrective CPR feedback, rescuers will ignore automated feedback prompts for deeper compressions when they subjectively feel that they have provided adequate force.²⁴ Rescuer fear of doing harm to the patient by delivering a CC that may ultimately be harmful is an ongoing issue and barrier to providing adequately deep CCs in all age groups. In our study, the mean compression force applied for the pre-puberty and post-puberty groups ($30.7 \text{ kg} \pm 7.6 \text{ kg}$, $33.6 \pm 9.4 \text{ kg}$, $p = 0.07$) was about the same as reported by Tomlinson et al. in their older adult population (median age 70 [IQR 61, 81]; mean force applied was $30.3 \pm 8.2 \text{ kg}$)²⁴ yet was lower than the mean $43.9 \pm 4.0 \text{ kg}$ as reported in the adult study (age range 25–76 years) by Gruben et al.²⁵ Maltese et al.'s study of the 8+ year old population (age range 8–22 years) demonstrated a comparable mean compression force of $30.9 \pm 5.5 \text{ kg}$.¹⁴ Interestingly, they noted that when plotting the stiffness of the chest with the adult data collected by Tsitlik et al.²⁶, the stiffness of the chest appears to increase from youth to middle age and then decrease in the elderly. The corresponding compression force required to reach a uniform compression depth across age would follow the same pattern. Evidence from a systematic review of pediatric CPR showed that rib fractures are rarely associated with CCs²⁷ suggesting that a deeper CC may be provided to the younger children without causing the minor injuries seen more frequently in the adult population.

The 2010 ILCOR consensus on science and 2010 AHA guidelines now recommend both absolute and relative APD CC depth targets in order to encourage improved depth of CC. Our data suggests that informed and experienced pediatric health care providers in tertiary care children's hospitals are not currently routinely achieving the recommended relative CC depth targets nor the actual CC depth targets in clinical practice. We speculate that the extension of reliable real-time audiovisual CPR feedback technology with actual depth measurements might facilitate code leader direction to have the team achieve deeper compressions for children of all ages.

5. Limitations

There are several limitations to this study. This investigation only included children 8 years and older, therefore, these findings cannot be confirmed as generalizable to younger children, however, there is no reason to believe the artificial cutoff of 8 years of age is physiologic. In addition, APD was not collected in 22% (11/50) of eligible resuscitations. These subjects had no difference in age or location of arrest. However, more subjects without measurements obtained ROSC which may account for the inability of staff to obtain measurements (i.e., the patient had just obtained ROSC, therefore the clinical team discouraged movement of the patient to obtain measurements). Regardless, we cannot guarantee that there was no selection bias. The CC depth achieved was guided by the clinical resuscitation team leader, augmented by accelerometer/force transducer real-time feedback that was not adjusted for mattress compensation real-time. The CC depth was guided by the code leader's assessment of appropriate CC depth for the patient based upon feedback from clinical signs, multiple monitors and devices as available for each patient. Since our current data do not allow us to specifically differentiate the alternatives available to the code leader for determining adequate CC depth, the target of the depth of compressions may not have been always intended to achieve compliance with AHA guidelines, but may have been titrated by individual team leaders to other vital signs or targets (e.g., nearly 40% of PICU subjects had invasive arterial lines). Therefore, further data capture to relate deeper depths of compression (relative and/or actual) with improved hemodynamics and outcomes are needed in both single center and multicenter settings. Additionally, this study was not intended nor adequately powered to associate depth of CC with outcome, therefore the results cannot be interpreted to support or refute this association. Additional multi-center investigation with appropriate power should be completed to

properly correlate the significance of CC depth with ROSC and mortality. Finally, we obtained chest APD measurements after CPR was complete which may have not been truly reflective of the natural chest dimension prior to chest compressions. It is possible that “molding” of the chest from CCs may have artificially reduced the APD measured, therefore potentially overestimating the relative APD.

6. Conclusions

This is the first systematic assessment of CC depths, reported both as relative % APD and actual depth, delivered to older children during actual CPR guided by experienced PICU and ED providers and available clinical monitoring in a children’s hospital setting. After compensation for mattress deflection, we found that 92% of CCs delivered to in-hospital cardiac arrest patients 8–14 years were $<1/3$ AP chest depth (the minimum pediatric CC recommendation at the time of data collection) and that 60% of those events had mean corrected CC depth of <38 mm (the minimum adult CC recommendation at the time of data collection). Mean CC actual depth and force were not significantly different in the pre-puberty and post-puberty groups. In our pre-pubertal population (8–14 years), a CC of 50 mm would compress 38% (6/16) of the subject chests to $>1/3$ APD, but would not reach $1/2$ APD in any of the subjects. Consequently, the use of a constant CC depth target of about 50 mm may not be harmful for this pediatric pre-pubescent (8–14 year old) population. There is opportunity to use feedback technology for actual or relative depth of compression to improve goal-directed compliance with 2010 AHA guidelines. Further data capture to relate deeper depths of compression with hemodynamics and outcomes is needed to determine the optimal CC depth for children and inform future CPR guidelines.

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References

1. Aufderheide TP, Yannopoulos D, Lick CJ, et al. Implementing the 2005 American Heart Association guidelines improves outcomes after out-of-hospital cardiac arrest. *Heart Rhythm*. 2010; 7:1357–62. [PubMed: 20420938]
2. Thigpen K, Davis SP, Basol R, et al. Implementing the 2005 American Heart Association guidelines, including use of the impedance threshold device, improves hospital discharge rate after in-hospital cardiac arrest. *Respir Care*. 2010; 55:1014–9. [PubMed: 20667148]
3. Nolan JP, Hazinski MF, Billi JE, et al. Part 1: executive summary: 2010 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations. *Resuscitation*. 2010; 81:e1–25. [PubMed: 20956042]
4. Wik L, Kramer-Johansen J, Myklebust H, et al. Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest. *JAMA*. 2005; 293:299–304. [PubMed: 15657322]
5. 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. [PubMed: 16982127]
6. Sutton RM, Niles D, Nysaether J, et al. Quantitative analysis of CPR quality during in-hospital resuscitation of older children and adolescents. *Pediatrics*. 2009; 124:494–9. [PubMed: 19581266]
7. Abella BS, Sandbo N, Vassilatos P, et al. Chest compression rates during cardiopulmonary resuscitation are suboptimal: a prospective study during in-hospital cardiac arrest. *Circulation*. 2005; 111:428–34. [PubMed: 15687130]

8. Abella BS, Alvarado JP, Myklebust H, et al. Quality of cardiopulmonary resuscitation during in-hospital cardiac arrest. *JAMA*. 2005; 293:305–10. [PubMed: 15657323]
9. Field JM, Hazinski MF, Sayre MR, et al. Part 1: executive summary: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation*. 2010; 122:S640–56. [PubMed: 20956217]
10. International Liaison Committee on Resuscitation. 2005 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations. *Circulation*. 2005; 112(Suppl 1):III-73–90.
11. Berg MD, Schexnayder SM, Chameides L, et al. Part 13: pediatric basic life support: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation*. 2010; 122:S862–75. [PubMed: 20956229]
12. Braga MS, Dominguez TE, Pollock AN, et al. Estimation of optimal CPR chest compression depth in children by using computer tomography. *Pediatrics*. 2009; 124:e69–74. [PubMed: 19564271]
13. Niles D, Sutton RM, Donoghue A, et al. Rolling refreshers: a novel approach to maintain CPR psychomotor skill competence. *Resuscitation*. 2009; 80:909–12. [PubMed: 19467759]
14. Maltese MR, Castner T, Niles D, et al. Methods for determining pediatric thoracic force-deflection characteristics from cardiopulmonary resuscitation. *Stapp Car Crash J*. 2008; 52:83–105. [PubMed: 19085159]
15. Aase SO, Myklebust H. Compression depth estimation for CPR quality assessment using DSP on accelerometer signals. *IEEE Trans Biomed Eng*. 2002; 49:263–8. [PubMed: 11876291]
16. Nishisaki A, Nysaether J, Sutton R, et al. Effect of mattress deflection on CPR quality assessment for older children and adolescents. *Resuscitation*. 2009; 80:540–5. [PubMed: 19342150]
17. 2005 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation*. 2005; 112(Suppl):IV1–203. [PubMed: 16314375]
18. Zuercher M, Hilwig RW, Ranger-Moore J, et al. Leaning during chest compressions impairs cardiac output and left ventricular myocardial blood flow in piglet cardiac arrest. *Crit Care Med*. 2010; 38:1141–6. [PubMed: 20081529]
19. Pickard A, Darby M, Soar J. Radiological assessment of the adult chest: implications for chest compressions. *Resuscitation*. 2006; 71:387–90. [PubMed: 16982125]
20. Kramer-Johansen J, Myklebust H, Wik L, et al. Quality of out-of-hospital cardiopulmonary resuscitation with real time automated feedback: a prospective interventional study. *Resuscitation*. 2006; 71:283–92. [PubMed: 17070980]
21. Ornato JP, Levine RL, Young DS, Racht EM, Garnett AR, Gonzalez ER. The effect of applied chest compression force on systemic arterial pressure and end-tidal carbon dioxide concentration during CPR in human beings. *Ann Emerg Med*. 1989; 18:732–7. [PubMed: 2500044]
22. Ristagno G, Tang W, Chang YT, et al. The quality of chest compressions during cardiopulmonary resuscitation overrides importance of timing of defibrillation. *Chest*. 2007; 132:70–5. [PubMed: 17550931]
23. Wu JY, Li CS, Liu ZX, Wu CJ, Zhang GC. A comparison of 2 types of chest compressions in a porcine model of cardiac arrest. *Am J Emerg Med*. 2009; 27:823–9. [PubMed: 19683111]
24. Tomlinson AE, Nysaether J, Kramer-Johansen J, Steen PA, Dorph E. Compression force–depth relationship during out-of-hospital cardiopulmonary resuscitation. *Resuscitation*. 2007; 72:364–70. [PubMed: 17141936]
25. Gruben KG, Guerci AD, Halperin HR, Popel AS, Tsitlik JE. Sternal force-displacement relationship during cardiopulmonary resuscitation. *J Biomech Eng*. 1993; 115:195–201. [PubMed: 8326726]
26. Tsitlik JE, Weisfeldt ML, Chandra N, Effron MB, Halperin HR, Levin HR. Elastic properties of the human chest during cardiopulmonary resuscitation. *Crit Care Med*. 1983; 11:685–92. [PubMed: 6884048]
27. Maguire S, Mann M, John N, Ellaway B, Sibert JR, Kemp AM. Does cardiopulmonary resuscitation cause rib fractures in children? A systematic review. *Child Abuse Negl*. 2006; 30:739–51. [PubMed: 16857258]

Fig. 1.
Corrected depth relative to APD for pre-puberty group (2005 AHA Guideline target depth 33–50% AP depth).

Fig. 2.

Boxplots displaying the distribution of anthropometric chest depths relative to APD for 8–14 years pre-puberty subjects (1/3 APD; 1/2 APD). The dotted lines represent the location of the 2005 adult (38 mm) and 2010 pediatric and adult (50 mm) chest compression minimum guideline targets. The upper adjacent value and the lower adjacent value described in horizontal lines (whiskers) indicate the highest and lowest values within 1.5 IQR from the 75th percentile and 25th percentile, respectively.

Table 1

Event demographics.

Event characteristic data (<i>n</i> = 35)	Pre-puberty (<i>n</i> = 16)	Post-puberty-adult (<i>n</i> = 19)
Age: years (mean $\pm$ SD, range)	11.9 $\pm$ 2.0, 8.1–14.9	18.0 $\pm$ 2.7, 15–24
Gender, <i>n</i> (%)		
Female	8 (50)	10 (53)
Male	8 (50)	9 (47)
Weight: kilograms (mean $\pm$ SD, range)	42.5 $\pm$ 7.9, 30–55	50.2 $\pm$ 13.6, 20–70
AP chest depth: mm (mean $\pm$ SD, range)	164.6 $\pm$ 25.1, 150–210	196.5 $\pm$ 30.4, 130–260
Location of arrest, <i>n</i> (%)		
Pediatric intensive care unit	7 (44)	14 (74)
Emergency department	9 (56)	5 (26)
Immediate cause of arrest, <i>n</i> (%; CI ⁹⁵)		
Hypotension	5 (31, 11–59)	10 (53, 29–76)
Arrhythmia	1 (6, 0–30)	4 (21, 6–46)
Inadequate or obstruction of airway	5 (31, 11–59)	3 (16, 0–40)
Unknown	2 (13, 2–38)	1 (5, 0–26)
Outcomes, <i>n</i> (%; CI ⁹⁵)		
Return of spontaneous circulation	4 (25, 7–52)	5 (26, 9–51)
Survival to hospital discharge	1 (6, 0–26)	1 (5, 0–30)

Table 2

Event characteristics of pre-puberty and post-puberty subjects.

Event #	Age (years)	Gender	ICA ^a	Body mass (kg)	AP chest depth (mm)	1/3 APD (mm)	% CC	1/3 relative	% CC	38 mm corrected	ROSC ^b	SHD ^c
<i>Pre-puberty (8–4 years) n = 16</i>												
1	8.1	F	Metabolic	40	150	50		0		0	Y	N
2	9.0	F	Inadeq Airway	40	190	63		0		1	N	N
3	9.6	F	Unknown	30	130	43		3		34	N	N
4	10.2	M	Unknown	33	130	43		13		17	N	N
5	10.4	F	Hypotension	33	150	50		15		31	N	N
6	10.4	F	Arrhythmia	40	150	50		43		96	Y	Y
7	12.0	M	Inadeq Airway	40	160	53		0		24	N	N
8	12.0	M	Inadeq Airway	40	160	53		0		1	Y	N
9	12.3	M	Hypotension	45	178	59		0		59	N	N
10	12.8	M	Metabolic	55	210	69		0		0	N	N
11	13.0	F	Inadeq Airway	40	170	56		20		94	N	N
12	13.0	M	Hypotension	40	155	51		33		94	N	N
13	13.5	F	Pulm Edema	45	140	46		0		34	Y	N
14	14.0	M	Inadeq Airway	60	190	63		0		46	N	N
15	14.5	M	Hypotension	50	160	53		0		0	N	N
16	14.9	F	Hypotension	48	210	69		0		74	N	N
<i>Post-puberty (15+ years) n = 19</i>												
17	15.0	F	Hypotension	37.0	130	43		76		84	N	N
18	15.1	F	Inadeq Airway	70.0	190	63		0		11	N	N
19	15.5	F	ARI ^d	35.0	185	62		0		0	N	N
20	15.8	F	Unknown	65.0	188	63		0		30	N	N
21	16.0	F	Hypotension	20.0	165	55		0		20	N	N
22	16.0	F	Hypotension	57.1	220	73		0		7	N	N
23	16.2	F	Inadeq Airway	39.9	165	55		2		24	N	N
24	16.9	M	Arrhythmia	55.0	203	68		0		70	Y	N
25	16.9	M	Inadeq Airway	55.0	203	68		0		77	N	N
26	17.0	F	Hypotension	55.0	170	57		0		63	N	N

Event #	Age (years)	Gender	ICA ^a	Body mass (kg)	AP chest depth (mm)	1/3 APD (mm)	% CC	1/3 relative	% CC	38 mm corrected	ROSC ^b	SHD ^c
27	17.0	F	Arrhythmia	53.0	210	70		0		82	N	N
28	18.1	M	Hypotension	57.1	200	67		0		10	Y	N
29	18.1	M	Arrhythmia	57.1	200	67		0		3	Y	N
30	19.0	M	Hypotension	70.0	205	68		6		98	N	N
31	19.0	M	Hypotension	45.0	200	67		0		2	N	N
32	21.0	M	Arrhythmia	54.0	200	67		0		47	Y	Y
33	22.3	M	Hypotension	50.0	260	87		0		28	N	N
34	22.9	F	Hypotension	25.0	260	87		0		6	N	N
35	24.0	M	Hypotension	53.0	180	60		14		60	Y	N

^aImmediate cause of arrest.

^bReturn of spontaneous circulation.

^cSurvival to hospital discharge.

^dAcute respiratory insufficiency.

Table 3

Stratified analysis by age category.

	8–4 years (<i>n</i> = 16)	15+ years (<i>n</i> = 19)	<i>p</i> -Value
Actual corrected CC depth (mm)	36.2 ± 9.6	36.8 ± 9.9	<i>p</i> = 0.64
Relative corrected CC depth (% to APD)	22.5 ± 7.0 (%)	19.5 ± 6.7 (%)	<i>p</i> = 0.13
Force (kg)	30.7 ± 7.6	33.6 ± 9.4	<i>p</i> = 0.07

Table 4

Chest compression depth (corrected) compliance with 2005 and 2010 AHA guidelines by age category.

	All ages	8–14 years	15+ years	<i>p</i> -Value [†]
38 mm criteria	40.6%	40.1%	41.1%	<i>p</i> = 0.49
1/3 APD criteria	6.4%	7.8%	5.2%	<i>p</i> = 0.002
50 mm criteria	9.6%	9.1%	10.1%	<i>p</i> = 0.53

[†] 8–14 years vs. 15+ years.

Table 5

Percentage APD corresponding to the 2005 (38 mm) and 2010 (50 mm) minimum chest compression guidelines by age category.

Compression depth	8–14 years, APD (%)	15+ years, APD (%)
38 mm	23.6 ± 3.5	19.8 ± 3.2
50 mm	31.0 ± 4.5	26.0 ± 4.3