WHAT’S KNOWN ON THIS SUBJECT: Rapid initiation of effective chest compressions (CCs) for patients in cardiac arrest improves outcomes, yet even trained rescuers fail to provide consistently effective CCs. Pediatric data on CC quality and objective measures of CC work are limited.

WHAT THIS STUDY ADDS: CC quality deteriorates similarly in pediatric and adult models, and overall work done to compress the pediatric chest is similar to that in adults. Power output during CC performance is analogous to that generated during intense exercise such as running.

abstract

BACKGROUND: Chest compression (CC) quality deteriorates with time in adults, possibly because of rescuer fatigue. Little data exist on compression quality in children or on work done to perform compressions in general. We hypothesized that compression quality, work, and rescuer fatigue would differ in child versus adult manikin models.

METHODS: This was a prospective randomized crossover study of 45 in-hospital rescuers performing 10 minutes of single-rescuer continuous compressions on each manikin. An accelerometer recorded compression quality measures over 30-second epochs. Work and power were calculated from recorded force data. A modified visual analogue scale measured fatigue. Data were analyzed by using linear mixed-effects models and Cox regression analysis.

RESULTS: A total of 88 484 compression cycles were analyzed. Percent adequate CCs/epoch (rate ≥ 100/minute, depth ≥ 38 mm) fell over 10 minutes (child: from 85.1% to 24.6%, adult: from 86.3% to 35.3%; P = .15) and were <70% in both by 2 minutes. Peak work per compression cycle was 13.1 J in the child and 14.3 J in the adult (P = .06; difference, 1.2 J; 95% confidence interval, −0.05 to 2.5). Peak power output was 144.1 W in the child and 166.5 W in the adult (P < .001; difference, 22.4 W, 95% confidence interval, 9.8–35.0).

CONCLUSIONS: CC quality deteriorates similarly in child and adult manikin models. Peak work per compression cycle is comparable in both. Peak power output is analogous to that generated during intense exercise such as running. CC providers should switch every 2 minutes as recommended by current guidelines. Pediatrics 2013;131:e797–e804

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KEY WORDS

cardiac arrest, cardiopulmonary resuscitation, chest compressions, rescuer fatigue, pediatric advanced life support, work, power

ABBREVIATIONS

AHA—American Heart Association
CC—chest compression
CI—confidence interval
CPR—cardiopulmonary resuscitation
C:V ratio—compression:ventilation ratio

(Continued on last page)
Cardiac arrests occur in 8 to 20 children per 100,000 per year and in 2% to 5.5% of patients admitted to PICUs. Outcomes are frequently poor despite regular updates and widespread dissemination of the pediatric advanced life support guidelines. Outcomes from in-hospital arrests have improved, with 27% of patients surviving to discharge. Conversely, out-of-hospital arrests have poorer outcomes, with only 12% survival to discharge, illustrating the importance of rapid access to appropriately trained in-hospital personnel.

High-quality chest compressions (CCs) remain the mainstay of circulatory support after cardiac arrest. Survival of patients after cardiac arrest is significantly improved with the provision of effective CCs, which increases coronary artery and cerebral perfusion. For this reason, current American Heart Association (AHA) guidelines for cardiopulmonary resuscitation (CPR) emphasize the performance of physiologically effective CCs. They focus on faster, deeper CCs with full chest recoil (avoiding leaning) and minimal interruptions.

Data in simulated and real patients demonstrate that laypersons, emergency medical services personnel, and health care providers frequently perform poor-quality CCs. Previous adult manikin studies document deterioration of CC quality with time, resulting in markedly diminished levels of effective CCs after as little as 1 minute. These studies also note that practitioners were unaware of their deterioration in performance and only reported subjective fatigue after 3 to 4 minutes of CCs. The suggestion from these early studies was that “rescuer fatigue” caused by the work required to perform adequate CCs could be a significant unrecognized factor contributing to poor CC quality. Current AHA CPR guidelines therefore call for compressors to be switched every 2 minutes to minimize fatigue and allow maintenance of high-quality CCs. However, this may inadvertently increase detrimental hands-off time, which adversely affects coronary perfusion, contributing to postresuscitation myocardial dysfunction.

Conversely, recent reports suggest that CCs can be performed for extended periods without significant deterioration in CC quality beyond AHA guidelines. Data on CC deterioration and rescuer fatigue in the pediatric setting are limited; the vast majority of studies and clinical recommendations are based on adult data. Our objective was to perform a comparative quantitative study evaluating CC quality, work associated with CC performance, and self-reported rescuer fatigue in child and adult manikin models. We hypothesized that CC quality would deteriorate less rapidly over time in the child model and that work performed in compressing the chest, as well as associated self-reported fatigue, would be lower in the child than in the adult model.

**METHODS**

**Design**

This prospective randomized crossover experimental trial was approved by the Institutional Review Board at the Children’s Hospital of Philadelphia. All study participants provided informed consent before enrollment. Data were collected in compliance with Health Insurance Portability and Accountability Act guidelines to ensure subject confidentiality.

**Subjects**

Male and female health care practitioners who routinely provide CCs at Children’s Hospital were recruited for enrollment. Lay practitioners, pregnant women, and those with significant chronic medical problems were excluded.

**Materials**

An adult and a 5-year-old child manikin (Resusci-Anne and Resusci-Junior; Laerdal Medical Corporation, Stavanger, Norway) were used. Quantitative measures of CC performance were obtained by using the HeartStart MRx Monitor/Defibrillator with quality CPR technology (Philips Healthcare, Andover, MA), which uses force-sensor/accelerometer technology to quantify rate, depth, deflection force, and residual leaning force during CCs. The device also provides real-time audiovisual feedback to the compressor, calibrated to appropriate depth and rate for adult CCs according to the 2005 AHA guidelines; this feature was used during the practice phase of each session (see below).

**Study Protocol**

Each participant was randomized (using random number generation) to 1 of 2 groups, varying only in order of manikins compressed: adult first versus child first. Each performed CCs on both manikins on 2 different days (separated by a minimum of 24 hours to limit residual fatigue), thereby serving as his/her own control. All participants had an initial 30 seconds of practice on the assigned manikin for the day with audiovisual feedback enabled. Subsequently, each had a 5-minute rest period followed by the experimental session during which each performed continuous CCs on the assigned manikin for a total of 10 minutes or until the point of maximal subjective fatigue. No audiovisual feedback was provided during testing sessions (to more closely simulate real-world resuscitations in which such feedback is generally not available). A modified visual analogue scale measured verbally self-
reported fatigue at 1, 2, 3, 5, 7, and 10 minutes during the experimental session. CCs were performed with the manikin on a backboard (59 × 50 × 1 cm) on a standard hospital stretcher at a height of 71 cm. Participants performed CCs in the standing position with or without the aid of a stepstool (participant choice; maximum stool height, 23.5 cm). Neither participants nor study personnel were blinded to the objectives of the study given the limited pool and their familiarity with the study (Fig 1).

CC data were analyzed in 30-second epochs by using quality CPR Review 2.0 (Laerdal Medical Corporation, Stavanger, Norway). Adequate CC depth was defined as ≥38 mm, and adequate CC rate was defined as ≥100 CCs/minute in both manikins. Outcomes of interest were CC depth, CC rate, leaning (defined as ≥2.5 kg residual force on the chest at the end of the release phase of each CC cycle), percent adequate CCs per epoch (CCs with adequate depth and rate and no leaning), force, work, power, and fatigue scores. Work was calculated from recorded chest deflection data and was defined as the maximum work value per individual CC cycle (from start to end of each CC). Power (work rate or work per unit time) was calculated as the derivative of work.

### Statistical Analysis

Srikantan et al23 previously compared compression:ventilation (C:V) ratios in manikins of the same sizes, reporting mean values of 62 and 56 CCs/minute in the child and adult manikins, respectively. Using a 2-group t test with a 2 × 2 crossover design, a .05 2-sided significance level, and a power of 80% to detect a difference in means of 6 CC/minute (assuming that the SD of differences is 13.8), we calculated that a sample size of 22 in each sequence group would be adequate (for a total sample size of 44).

Descriptive statistics of participant demographics, CC quality measures for each manikin (depth, rate, leaning, and percent adequate CCs), work data (force, work, power), and self-reported fatigue (duration of compressions, visual analogue scale scores) were calculated. Differences between the 2 manikin models per 30-second epoch over the 10-minute experimental session with respect to CC quality measures and work data were analyzed by using linear mixed-effects models, accounting for crossover design and repeated measurements within subjects. The association between fatigue scores and number of adequate CCs/minute were also analyzed by using linear mixed-effects models. Cox regression analysis was applied to assess the relationship between fatigue scores and <70% adequate CCs (on the basis of expert consensus), with fatigue as the time-dependent covariate.

### RESULTS

#### Participant Characteristics

Forty-five participants completed the study, yielding 1492 epochs of compression data with 88,484 compression cycles. Thirty-one (69%) were women, and 28 (62%) were physicians. Mean age and BMI were 34.4 years and 25.2, respectively. Thirty-three participants (73%) elected to use a stepstool for the child manikin session, and 38 (84%) used one for the adult (P = .64; Table 1). Mean duration of CCs was 8.2 ± 2.7 minutes in the child and 8.0 ± 3.0 minutes in the adult (P = .71), with 28 participants (62.2%) compressing for the full 10-minute experimental period in the child and 26 (57.8%) performing for the same duration in the adult.

#### CC Quality

Mean CC rate increased in both manikin models over 10 minutes (child: from 106 to 117.5 CCs/min, adult: from 104.5 to 118 CCs/min; P = .49) but remained within current AHA CPR guidelines (≥100 CCs/minute) throughout (Fig 2).

Mean CC depth decreased over 10 minutes in both (child: from 41.3 to 33.6 mm, adult: from 42.3 to 35.6 mm; P = .07) but was maintained ≥38 mm for 3 minutes in the child and 4 minutes in the adult (Fig 3). Leaning increased from 3.2 to 10.8 CC/epoch over 10 minutes in the
Mean number of adequate CCs per epoch (number of CCs with depth ≥38 mm, rate ≥100 CC/min, and no leaning per 2005 AHA CPR guidelines) decreased from 42 to 12.1 in the child and 38 to 18.1 in the adult. This measurement decreased faster in the child than in the adult, with a mean rate of decrease of 3.3 adequate CCs/minute in the child and 2.0 adequate CCs/minute in the adult (P = .02).

Mean percent adequate CC per epoch fell from 85.1% to 24.6% over 10 minutes in the child and was <68% after 90 seconds. For the adult, corresponding values were 86.3% to 35.3% over 10 minutes and <69% after 120 seconds (P = .15; Fig 4).

**Work Data**

Peak force applied to the manikin chest was 337.2 N in the child and 353.0 N in the adult (P = .05; difference, 15.8; 95% confidence interval [CI], 20.1 to 31.7). Peak work per compression cycle was 13.1 J in the child and 14.3 J in the adult (P = .06; difference, 1.2; 95% CI, 20.05 to 2.5). Peak power output was 144.1 W in the child and 166.5 W in the adult (P < .001; difference, 22.4; 95% CI, 9.8 to 35.0).

**Self-Reported Fatigue**

Mean fatigue scores increased over 10 minutes in both manikins from 2.3 to 8.2 in the child and from 2.7 to 8.2 in the adult and were 4.0 and 4.2, respectively, at 2 minutes. The estimated decrease of percent adequate CCs per unit increase of fatigue score was 2% (P = .03). However, there was no relationship found between fatigue scores and time to <70% adequate CCs (P = .14; Fig 5).

**DISCUSSION**

Given previous data suggesting that fatigue caused by work done by the rescuer during CC performance affects the quality of CCs, our intention was to quantify and evaluate CC quality, work associated with CC performance, and subjective rescuer fatigue in child and adult manikin models. We compared detailed measures of CC quality between the 2 models, an area where few data are available. Our results demonstrate that the pattern of CC deterioration was similar for adult and child models for this population of trained in-hospital providers. CC depth clearly decreased from 3.8 to 12.2 CC/epoch in the child (P = .25).

Mean number of adequate CCs per epoch (number of CCs with depth ≥38 mm, rate ≥100 CC/min, and no leaning per 2005 AHA CPR guidelines) decreased from 42 to 12.1 in the child and 38 to 18.1 in the adult. This measurement decreased faster in the child than in the adult, with a mean rate of decrease of 3.3 adequate CCs/minute in the child and 2.0 adequate CCs/minute in the adult (P = .02).

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decreases with time in both models, despite the fact that CC rate was maintained at guideline-consistent rates of ≥100 CCs/minute over the 10 minutes of continuous CCs. Leaning also increased similarly in both models. Because of these factors, percent adequate CCs per minute was ≤70% after 2 minutes of single rescuer continuous CCs in either model. The only significant difference in CC quality measures between the adult and child manikins was the faster decrease in the child of mean number of adequate CCs per epoch, possibly because of the underestimation by the rescuers of the effort required to maintain effective compressions in the child. The fact that overall CC depths in the child were persistently lower (although not statistically significant) despite subjects being trained to compress to a depth of ≥38 mm for both manikins supports this. We also show that, although the peak force applied was higher in the adult than in the child manikin, the difference in peak work performed per CC cycle in each was not statistically significant. This finding is consistent with the fact that CC depth was also not statistically different between the two (given that work = force × distance moved). Peak power (work per unit time or work rate) did significantly differ between the 2 manikins, with more power being generated per CC in the adult than in the child, suggesting that the mechanism by which participants achieve adequate depth may differ between the adult and child manikins, but overall exertion remains similar. Interestingly, our data suggest that peak power output during performance of CCs is comparable to that generated during intense exercise such as running (154 W for a 70-kg man running on a level surface at 9 km/hour) or swimming (158 W for a 70-kg man swimming at high intensity in a pool), illustrating that the correct performance of CCs requires significant levels of exertion in either model.

Self-reported fatigue increased similarly in both manikin models. Participants identified fatigue, but their reported levels of fatigue were low compared with the decrease in CC quality over the first 2 minutes of CCs and did not correlate well with CC deterioration during that period. This finding is consistent with earlier findings indicating that rescuers overestimated their duration of adequate CCs and reported fatigue minutes after onset of significant CC deterioration. Unlike these reports, however, we did find a correlation between CC quality and fatigue scores over the entire 10-minute study period. Multiple studies in real and simulated adult cardiac arrest scenarios have established the decrease in CC quality with time. Pediatric data on the same subject are slowly emerging. For actual adult in-hospital arrests, Sugarman et al demonstrated a decrease in CC depth by 90 seconds that continued over 3 minutes of continuous single rescuer CC (with maintenance

![FIGURE 4](Image of Figure 4)

**FIGURE 4**
Mean percent adequate compressions per epoch.

![FIGURE 5](Image of Figure 5)

**FIGURE 5**
Self-reported fatigue scores over the 10-minute experimental session.
of CC rate ≥ 100/minute) despite real-time audiovisual feedback aimed at maintaining effective CCs, implying that rescuer fatigue was a major contributing factor in CC deterioration. Sutton et al.26 in their seminal report of CC quality in real in-hospital pediatric arrests, revealed that 2005 AHA guideline—recommended targets were only achieved in 63.9% of studied time segments for depth and 56.9% for rate. Findings from both studies likely underestimate the presence of inadequate CCs and extent of CC decay in real-world settings given that both were conducted with real-time audiovisual feedback. We have attempted to simulate real-world settings in which such real-time feedback is not routinely available.

Despite the many adult reports of CC decay with time for single rescuers performing continuous CCs, Bjrøshol et al.27 recently reported minimal rates of CC decay in a simulated (adult) manikin model of continuous CCs over 12 minutes. The authors found a significant amount of inherent variability in the ability of trained paramedics to perform adequate CCs. Decay was noted in 26% and 37% of episodes based on depth and rate, respectively. However, as many as 47% performed bad CCs from the initiation of the resuscitation attempt (on the basis of depth), implying that variability in rescuers’ abilities may contribute more to poor CC quality than fatigue. We attempted to eliminate this confounding factor by ensuring that all enrolled participants demonstrated adequate CC quality in the 30-second practice session (during which audiovisual feedback was given) just before initiation of each study session. Despite demonstration of adequate technique initially, we noted decay (albeit at differing rates) for all participants during each study session.

Very few reports comparing CC quality in adult and pediatric models exist in the literature. Srikantan et al.23 in their single rescuer manikin study of varying C:V ratios in adult, child, and infant manikins, found that effective CCs and ventilations per minute were lower in the child manikin than in the adult counterpart. Haque et al.28 in another study primarily evaluating the effect of 2 C:V ratios on CC quality and rescuer fatigue using similar manikins, showed secondarily that CC rates were maintained at ≥100 CCs/minute over 5 minutes; however, no subjects achieved 2005 AHA recommended compression depths in the adult manikin. Both studies reveal differences in CC quality between manikins, but neither was able to quantify the work done on each manikin, which may have contributed to these differences. To our knowledge, the current study is the first to investigate differences in quantitative work between adult and child manikins, illustrating that the mean work per CC cycle was surprisingly similar in both models. Our results suggest that exertion required to compress the child chest adequately is similar to that in adults.

In addition, our results support the switching of compressors every 2 minutes in both child and adult resuscitations as recommended by AHA CPR guidelines given the similar deterioration of CC quality observed in both.

Our study had several limitations, most important of which is the fact that this was a simulated manikin study. Pediatric manikins, unlike adult manikins, may not be constructed with realistic chest stiffness and recoil and are thus not truly biofidelic because of the relative lack of data available on the compliance of the pediatric thorax. This phenomenon would limit the applicability of fatigue and CC quality results obtained on manikins to actual pediatric patients. It, however, likewise implies that we are not adequately able to train compressors in a realistic manner. Another limitation is the fact that we did not provide audiovisual feedback continuously in our effort to simulate real-world in-hospital arrests. Providing this may have improved CC quality and allowed us to more objectively quantify work done in performing adequate CCs. In addition, our measurements and equipment were calibrated to 2005 AHA guidelines because this study was initiated before the publication of the 2010 AHA guidelines. However, even at the shallower depths specified by the 2005 guidelines, we showed that a significant amount of exertion is required to perform CCs. Finally, participants may have performed more effectively because they were conscious of being observed (Hawthorne effect) or because they were not blinded to study objectives. Conversely, they may have performed less effectively because of the absence of the heightened emotional and physiologic responses that may be present in a real code situation.

CONCLUSIONS

In summary, we demonstrated that the pattern of CC deterioration is similar in child and adult models for a population of trained in-hospital providers. We confirm that CCs can be maintained at guideline consistent rates of ≥100 CCs/minute for up to 10 minutes of continuous CCs, but CC depth decreases with time during continuous CC performance. Percent adequate CCs per minute was <70% after 2 minutes of single rescuer continuous CCs in both models. We
also show that significant exertion, similar to that expected for high-intensity exercises such as running and swimming, is required to perform CCs. These findings support current AHA recommendations to switch compressors every 2 minutes in both pediatric and adult resuscitations. Further investigations into techniques for achieving adequate CC depth should be undertaken because this is a recurrent cause of inadequate CCs. In addition, pediatric chest wall compliance in real arrest scenarios should be studied to aid in developing appropriately biofidelic manikins. Results will bring us nearer to the goal of closing the gap between in- and out-of-hospital pediatric arrest survival and improving overall outcomes for both.

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ARTICLES

Dr Badaki-Makun conceptualized the idea, designed the study, and was primarily responsible for overseeing data acquisition, data analysis, interpretation of data, and manuscript preparation. She drafted the initial manuscript, revised it critically, and produced the final version to be published. Dr Nadel made substantial contributions to the design of the study, assisted in the interpretation of data, and revised the manuscript critically for important intellectual content, giving approval for the version to be published. Dr Donoghue made substantial contributions to the design of the study, assisted in the interpretation of data, revised the manuscript critically for important intellectual content, and gave approval of the manuscript to be published. Dr McBride made substantial contributions to the design of the study, especially with respect to the physiologic measures of work and energy expenditure. He assisted in the collection and interpretation of data related to these measures, revised the manuscript critically for important intellectual content related to this, and gave approval of the manuscript to be published. Ms Niles contributed to the design of the study, specifically with respect to the CPR quality measures. She assisted in the collection and interpretation of data related to these measures, revised the manuscript critically for important intellectual content related to these measures, and gave approval of the manuscript to be published. Mr Seacrist made substantial contributions to the analysis and interpretation of data related to work, power, and forces applied to the manikin chest. He revised the manuscript critically for important intellectual content and gave approval of the manuscript to be published. Mr Maltese made substantial contributions to the analysis and interpretation of data related to work, power, and forces applied to the manikin chest. He revised the manuscript critically for important intellectual content and gave approval of the manuscript to be published. Ms Zhang made substantial contributions to statistical methods in study design. She performed the majority of statistical analyses for all data collected in the study, assisted in the interpretation of these data, evaluated their statistical significance, and revised the manuscript critically for statistical methods. She gave approval of the manuscript to be published. Dr Paridon contributed to the design of the study, especially with respect to the physiologic measures of work and energy expenditure. He assisted in the collection of data related to these measures, revised the manuscript for important intellectual content related to these measures, and gave approval of the manuscript to be published. Dr Nadkarni oversaw the implementation of the study from start to finish, made substantial contributions to the design of the study, had significant input in the interpretation of all data obtained, revised the manuscript critically for important intellectual content, and gave approval of the manuscript to be published.

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