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TITLE: EFFECT OF MATTRESS DEFLECTION ON CPR QUALITY ASSESSMENT FOR OLDER CHILDREN AND ADOLESCENTS

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Abstract

Appropriate chest compression (CC) depth is associated with improved CPR outcome. CCs provided in-hospital are often conducted on a compliant mattress. The objective was to quantify the effect of mattress compression on the assessment of CPR quality in children.

Methods:

A force deflection sensor (FDS) was used during CPR in the Pediatric Intensive Care Unit and Emergency Department of a children's hospital. The sensor was interposed between the chest of the patient and hands of the rescuer and measured CC depth. Following CPR event, each event was reconstructed with a manikin and an identical mattress/backboard/patient configuration. CCs were performed using FDS on the sternum and a reference accelerometer attached to the spine of the manikin, providing a means to calculate the mattress deflection.

Results: 12 CPR events with 14,487 CC (11 patients, median age 14.9 years) were recorded and reconstructed: 9 on ICU beds (9296 CC), 3 on stretchers (5191 CC). Measured mean CC depth during CPR was 47±8mm on ICU beds, and 45±7mm on stretcher beds with overestimation of 13±4 mm and 4 ±1mm, respectively, due to mattress compression. After adjusting for this, the proportion of CC that met the CPR guidelines decreased from 88.4 to 31.8 % on ICU beds ($p<0.001$), and 86.3 to 64.7 % on stretcher ($p<0.001$). The proportion of appropriate depth CC was significantly smaller on ICU beds ($p<0.001$).

Conclusion: CC conducted on a non-rigid surface may not be deep enough. FDS may overestimate CC depth by 28% on ICU beds, and 10% on stretcher beds.

1. Background

Quality of cardiopulmonary resuscitation (CPR) is critical for survival and good neurological outcome from cardiopulmonary arrest. The Guidelines by the American

Heart Association (AHA) and International Liaison Committee on Resuscitation (ILCOR) published in 2005 emphasize the quality of CPR by 5 key points: push hard, push fast, minimize interruption, allow full chest recoil (e.g. release completely), and do not over-ventilate[1]. Several studies of adult in-hospital and out-of-hospital CPR confirmed these guidelines by linking quality of CPR measures with patient survival outcomes.[2-5]

Recent technology provides CPR providers with real-time directive and corrective feedback on the quality of CPR provided using force transducer and accelerometer technology. This feedback is based on the current guidelines and facilitates timely self-correction.[6-8] One of the most important parameters on which feedback is given is the depth of the chest compression (CC). Current automated feedback systems use AHA recommended criteria of 38 to 51 mm CC depth.[1-3] The corrective feedback is given by visual cue (the provided CC depth with the targeted range) and by audio (verbal) cue if the provided compression does not meet criteria for five consecutive compressions.

For in-hospital settings, CCs are often conducted on a compliant mattress, which may deform during the compression. This deformation may lead to overestimation of actual CC depth either via the perception of the provider or through guidance by CPR quality assessment technology described above that does not account for the compressibility of the mattress beneath the patient.

We hypothesized that compression of the mattress during in-hospital CPR resulted in an overestimation of the actual patient's CC depth as measured by quantitative CPR quality assessment technology. The objective of this study was to utilize novel technology and forensic engineering techniques to quantify the effect of mattress compression on the assessment of CPR quality in children. This approach allowed the calculation of the actual patient CC depth adjusted for the mattress compression.

2. Method

This study was conducted at the Children's Hospital of Philadelphia. Institutional Review Board approved data collection procedures, which were completed in compliance with the Health Insurance Portability and Accountability Act to ensure subject confidentiality. Written informed consent was obtained from all healthcare providers participated in the resuscitation attempts. Consent from patient/families was not required, because the data collection was primarily focused on the quality of provider CPR performance. Once a CPR event occurred, the ICU staff notified the research team immediately. This system was active for 24 hours a day, 7 days a week for any CPR event in ICU and Emergency Department (ED).

CPR data collection with FDS:
A force and deflection sensor (FDS) was integrated into a patient monitor-defibrillator (Philips Heartstart MRx with Q-CPR technology, Phillips, Andover, MA) used during CPR for children age 8 and older in the Pediatric Intensive Care Unit (PICU) and ED of a

children's hospital. The use of corrective audiovisual feedback system with FDS was used in patients who required CCs for severe bradycardia, hypotension or loss of spontaneous circulation according to Pediatric Advanced Life Support guidelines. The FDS was placed over the mid to lower half of the sternum of the patient beneath the hands of the rescuer providing CC, and CC was applied over the FDS. Because the FDS technology is based on measuring acceleration, the depth calculated by the FDS represents the movement of the FDS itself[9,10] relative to the ground, not only the deflection of the chest. 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.[11] The CC data, including average rate and actual number of CC delivered, depth (mm), force (kg), and type and time of audiovisual feedback prompts provided during CPR event was collected in the defibrillator, and were later downloaded.

Staff Education:

More than 90% of healthcare providers in the PICU and ED received extensive in-service training for the defibrillator and its quality-CPR automated realtime feedback function using FDS prior to patient use. This rigorous training consisted of completing a checklist of competencies, performing high quality CPR using the FDS on an adult CPR manikin, and receiving periodic, brief retraining sessions ("Rolling Refreshers") at the point of care.[12] The code team was extensively trained so that automated feedback was only used for patients ≥8 years old as an adjunct to clinical team and code leader's directions, and assisted the code leader/clinical team in directing resuscitation interventions and CPR quality.

CPR event forensic engineering reconstruction:

Once the CPR event was completed, the bed and mattress or the stretcher was tagged and held for CPR event reconstruction. The following information was recorded: position of the backboard on the bed/stretcher, position of the patient on the backboard, the mid-sternum chest depth and circumference at the nipple line, and patient weight. A standard CPR backboard (59cm X 50.5cm X 1cm) was used for all clinical CPR events.

The CPR event reconstruction was performed as follows: The manikin torso (Resusci Anne, Laerdal Medical, Stavanger, Norway) was placed onto a CPR backboard with an estimated torso weight of the patient (Figure 1). The torso weight was estimated as 1/2 of body weight based on the current literature.[13,14] The CPR board placement and the patient location on the bed/mattress were reproduced based on the data collected after the actual resuscitation. The FDS was placed over the manikin chest, and a reference accelerometer was placed on the spine of the manikin which provided a means to directly calculate the deflection of the mattress. Fifty CCs were performed on the manikin chest using the FDS to collect force and mattress deflection. Based on this data, we calculated the stiffness of the patient support system (bed and mattress).[9,10] In combination with the sternal force measured during the clinical event, we were able to estimate the actual deflection of the mattress during resuscitation. To estimate the actual CC depth of the patient, this mattress deflection was subtracted from the measured total compression depth. The detailed calculation method for mattress deflection is described in the Appendix.[11]

Bed and mattress systems:

Three different bed and mattress combinations were used in the PICU and one type of stretcher was used in the ED. The most commonly used combination in PICU was Hill Rom Advanta ICU Bed (Hill Rom, Batesville, IN) with Maxifloat LFP mattress (BG Industries, Northridge, CA).[15] Occasionally an air-filled mattress (Hill Rom Acucair surface) was inserted under the patients on top of the mattress.[16] A Triadyne Bed (KCI, San Antonio, Texas) was occasionally used for patients with high risk for decubitus. An air-filled mattress is a part of the Triadyne Bed, which was deflated during the CPR event.[17] The only system used in ED was a stretcher with a thin mattress (70mm): Hausted Horizon (STERIS, Corporation, Mentor, OH).

Data analysis:
In this study, we defined appropriate CC depth as ≥38 mm. Current AHA guidelines recommend CC depth of 38mm to 51mm.[1,3,4] Based on Edelson's in-hospital report[5], we did not consider an upper limit for adequate CC depth. The primary outcome was the proportion of CCs with adequate depth (≥38 mm) throughout an entire CPR event. This proportion was compared before and after the mattress/bed correction and between the two bed types (ICU bed and stretcher bed). Statistical analysis was performed by using STATA 10.0 (Stata Corporation, College Station, TX). Parametric variables were described by mean and standard deviation. Non-parametric variables were described by median and interquartile range. Fisher's exact test was used for categorical variables. McNemar test was used for paired categorical variables. T-test was used to compare parametric variables. Power calculation was not done *a priori* since this study was designed as a pilot descriptive study.

3. Results

From September 2006-July 2007, a total of 13 CPR events occurred in 12 patients ≥8 years old with CCs for more than one minute because of poor perfusion, severe bradycardia or loss of spontaneous circulation in the PICU or ED. The majority (9/13) were in the PICU. Among those events, FDS was used during resuscitation in 12 events (11 patients), with 14487 CCs (202-4356 for each event). The median age of the patients was 14.9 years (Interquartile range: 12.9-16.5). Table 1 summarizes patient demographic data and CPR events.

Table 2 describes the mattress/bed condition and CC measurement. Nine events occurred on the ICU beds. Eight events were on a Hill Rom Advanta ICU Bed with Maxifloat mattress, and 1 event on a Triadyne Bed with the mattress deflated. Two subjects (subject 6 and 8) had an air-filled mattress topper between the patient and the mattress at the time of CPR events. Three events occurred on Steris Stretcher in ED. CC force and depth data were collected for all 12 events; however, the real time audiovisual corrective feedback system was not used in one case (event 6).

The mean CC depth measured by the FDS during CPR events ranged from 37mm to 52mm in events on ICU beds (overall mean 47 ± 8mm), and 42mm to 47mm in events on stretchers (overall mean 45 ± 7mm). The difference between the two bed types (ICU beds with mattresses vs. ED Stretcher) was statistically different (p <0.0001, two sample t-test). This difference remains highly significant even after we excluded the event on the Triadyne bed with deflated mattress (47 ± 8mm vs. 45 ± 7mm, p<0.0001), and after we further excluded events with an extra air-filled mattress between the patient and mattress (47 ± 8mm vs. 45 ± 7mm, p<0.0001).

The mean CC force was 34 ± 8 kg for events on ICU beds and 26 ± 8 kg for events on stretchers. The mean calculated stiffness of the bed and mattress system was 2.7 ± 0.6 kg/mm for ICU beds and mattresses combined and 6.0 ± 1.0 kg/mm for stretchers. Figure 2 displays the stiffness at the maximal CC depth.

Overall mean mattress compression calculated from the CPR reconstruction was 13 ± 4 mm for the ICU beds and 4 ± 1 mm for stretcher beds, respectively. After compensating for the mattress deflection component, the corrected mean CC depth was 35 ± 6mm during events on ICU beds and 41 ± 7mm during events on stretchers. Both compensated values were significantly less than the uncompensated CC depths (p<0.0001 for both, paired t-tests) (Figure 3). The corrected CC depth on hospital beds was significantly less than the corrected CC depth on stretchers (p<0.0001).

On ICU beds, the proportion of CCs with adequate depth was 88.4 % before the compensation for mattress compression, and 31.8 % after the compensation (p<0.0001, McNemar test). On stretchers, the proportion of CCs with adequate depth before compensation was 86.3 % and 64.7% after the compensation (p<0.0001). The proportion of CCs with adequate depth after mattress compensation was significantly less on ICU beds compared to the events on stretchers (p<0.001, Fisher's exact test). Those results remained significant after we excluded the event on the Triadyne bed with deflated mattress, and after we excluded events with an extra air-filled mattress between the patient and mattress (p<0.0001 for both analysis).

4. Discussion

In this study, we report the corrected CC depth during actual in-hospital CPR in older children and adolescents. When measured with an accelerometer on the sternum of the cardiac arrest victim, realistic forensic engineering reconstruction of events revealed the deflection of the mattress contributes approximately 28% of measured CC depth on ICU beds and 10% of measured CC depth on stretchers with back boards in place. The corrected CC depth with mattress compensation more accurately represents the true depth of CC and quality of CPR. The proportion of CC with appropriate depth decreased significantly after compensating for the mattress deflection.

Traditionally the effect of mattress deflection has been ignored during real in-hospital CPR. Recent clinical studies analyzed quality of CPR in actual resuscitation, but did not consider the mattress deflection.[3-5] Even without considering mattress deflection during CPR, the reported CC depth described herein was often too shallow. In the first two quality of CPR studies with use of FDS as data collection method, shallow CCs were observed in 37.4% of compressions during in-hospital adult CPR and in 59% of compressions during out-of-hospital adult CPR. The mean CC depth was 42 mm during in-hospital and 35mm during out-of-hospital CPR.[3,4] Those differences can be attributable largely to presumed differences in compliance in mattress support systems (hospital bed in the former, and the stretcher/floor surface in the latter). If the data were compensated for mattress deflection, the reported CC depth would be even shallower especially in in-hospital CPR. In our study, the measured CC depth was larger than reported in those two studies. Intensive initial and refresher training, and real time feedback with FDS technology all perhaps contributed to this difference.

In this study, we chose to use the minimum threshold for adequate compression depth to be 38 mm as recommended for adult CPR guidelines. The smallest chest anterior-posterior (AP) diameter was 14cm in event 3. If we chose to use pediatric guidelines (1/3 of AP diameter as the minimum threshold for adequate compression depth) in our young patients, the threshold would have been much more strict (46mm).

At least two clinical studies demonstrated a positive association between the CC depth and CPR outcome.[6,7] Kramer-Johansen reported in adult out-of-hospital CPR that each 1 mm increment of CC depth was associated significantly with improved hospital admission rate.[6] Edelson reported in adult in-hospital and out-of-hospital CPR, each 5 mm increment of CC depth was associated with improved shock success for ventricular fibrillation.[5] This relationship has also been shown in an animal experimental model.[18] Babbs reported a positive linear relationship between compression depth and cardiac output when compression depth is beyond a certain threshold. Based on those studies, even a small incremental improvement in CC depth would be clinically significant. Therefore, we believe the decrease of CC depth after adjustment for mattress compression may be clinically important.

Use of a backboard during in-hospital CPR is recommended to 'minimize' the mattress deflection;[1] however, very few studies have evaluated the effect of the backboard. Perkins evaluated the effect of a backboard on CC depth with a manikin using internal depth measurement (VAM software) and external measurement by an accelerometer.[19] He reported the backboard increased actual CC depth by 1.9-2.6mm. Most other studies used a manikin equipped with internal depth measurement device, and so far those study results are equivocal.[20-22] The issue of whether backboards are effective requires further investigation. In addition, the impact of backboard size, type, and placement are fertile areas for further investigation.

Our study demonstrated the substantial effect of the support system under the patient on the actual depth of CCs and on the degree of overestimation of the quality of CPR based on the FDS placed on the sternum during real CC. The softer (less stiff) ICU bed and standard mattress combination was associated with shallower true CCs and larger overestimation by quality of CPR feedback systems, compared to stretchers with a thin mattress. Furthermore, the difference between actual CC depths and measured (unadjusted) CC depth among the various types of hospital beds (deflated Triadyne bed, ICU bed with an air mattress, and ICU bed with a standard mattress) were much larger compared to the CPR events on ED stretchers. Those findings were consistent with Perkins's study.[23] He reported significantly shallower mattress compensated compressions in adult manikins on foam (35.2±5.6 mm), inflated (37.2±6.3mm), and deflated (39.1±5.6 mm) mattresses compared to the hard-surface floor (44.2±5.2mm) by using a manikin with an internal depth measurement device. He speculated this significant difference may be due to: 1) use of the constant displacement model by chest compressors (i.e., compressors unintentionally attempt to provide the same chest compression depth measured from surface of the chest despite the mattress deflection), 2) presence of manikin on a hospital bed *per se* impairs CC delivery. Although both of these explanations probably contributed to our observation, our experimental design does not allow further clarification.

Our study results need to be interpreted in light of several important limitations. During CPR typically multiple providers performed CCs. We did not record and control for provider characteristics, previous training status and demographic data for those who provided CCs. It is possible that the automated directive and corrective feedback system guided the CC providers to compress too shallow, because the automated audiovisual feedback system is derived from the uncorrected CC depth measured by FDS. However, a recent study showed the CC depth without feedback is actually shallower than compression depth with such feedback.[6] The mattress deflection was not directly measured with a reference accelerometer simultaneously on the bed during the real CPR event, rather it was estimated based on the measured force applied during CPR events and on the mattress stiffness model using the compression depth and the applied force during forensic engineering reconstruction. However, forensic reconstruction of the events was conducted using the actual bed that was used during real CPR, with the size, shape and placement of the backboard precisely reproduced to minimize artifacts.
Although the error in FDS depth measurement on adult cadaver and manikin is within 3 mm, there is no FDS depth measurement accuracy data in children.

5. Conclusions

Realistic forensic engineering reconstruction of in-hospital pediatric CPR events suggests that deflection of the mattress contributes approximately 28% of measured CC depth on ICU beds and 10% of measured CC depth on stretchers with back boards in place, resulting in overestimation of CC depth by 13±4 mm on ICU beds, and 4 ±1mm on stretcher beds. CCs conducted on a non-rigid surface such as an ICU mattress bed or Emergency Department stretcher bed may not be deep enough. This finding suggests that quantitative CPR feedback systems could benefit from technologies to compensate for mattress compression artifact.

6. Conflict of Interest

This study was supported by Laerdal Foundation for Acute Care Medicine Grant and Endowed Chair, the Children's Hospital of Philadelphia

7. Acknowledgements

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