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

3
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16
17
18 **Abstract**

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

23 **Methods:**

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

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

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

41
42
43 **1. Background**

44
45 Quality of cardiopulmonary resuscitation (CPR) is critical for survival and good
46 neurological outcome from cardiopulmonary arrest. The Guidelines by the American

47 Heart Association (AHA) and International Liaison Committee on Resuscitation
48 (ILCOR) published in 2005 emphasize the quality of CPR by 5 key points: push hard,
49 push fast, minimize interruption, allow full chest recoil (e.g. release completely), and do
50 not over-ventilate¹. Several studies of adult in-hospital and out-of-hospital CPR
51 confirmed these guidelines by linking quality of CPR measures with patient survival
52 outcomes.²⁻⁵

53
54 Recent technology provides CPR providers with real-time directive and corrective
55 feedback on the quality of CPR provided using force transducer and accelerometer
56 technology. This feedback is based on the current guidelines and facilitates timely self-
57 correction.⁶⁻⁸ One of the most important parameters on which feedback is given is the
58 depth of the chest compression (CC). Current automated feedback systems use AHA
59 recommended criteria of 38 to 51 mm CC depth.¹⁻³ The corrective feedback is given by
60 visual cue (the provided CC depth with the targeted range) and by audio (verbal) cue if
61 the provided compression does not meet criteria for five consecutive compressions.

62
63 For in-hospital settings, CCs are often conducted on a compliant mattress, which may
64 deform during the compression. This deformation may lead to overestimation of actual
65 CC depth either via the perception of the provider or through guidance by CPR quality
66 assessment technology described above that does not account for the compressibility of
67 the mattress beneath the patient.

68
69 We hypothesized that compression of the mattress during in-hospital CPR resulted in an
70 overestimation of the actual patient's CC depth as measured by quantitative CPR quality
71 assessment technology. The objective of this study was to utilize novel technology and
72 forensic engineering techniques to quantify the effect of mattress compression on the
73 assessment of CPR quality in children. This approach allowed the calculation of the
74 actual patient CC depth adjusted for the mattress compression.

75

76 **2. Method**

77

78
79 This study was conducted at the Children's Hospital of Philadelphia. Institutional Review
80 Board approved data collection procedures, which were completed in compliance with
81 the Health Insurance Portability and Accountability Act to ensure subject confidentiality.
82 Written informed consent was obtained from all healthcare providers participated in the
83 resuscitation attempts. Consent from patient/families was not required, because the data
84 collection was primarily focused on the quality of provider CPR performance. Once a
85 CPR event occurred, the ICU staff notified the research team immediately. This system
86 was active for 24 hours a day, 7 days a week for any CPR event in ICU and Emergency
87 Department (ED).

88

89 *CPR data collection with FDS:*

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

93 children's hospital. The use of corrective audiovisual feedback system with FDS was
94 used in patients who required CCs for severe bradycardia, hypotension or loss of
95 spontaneous circulation according to Pediatric Advanced Life Support guidelines. The
96 FDS was placed over the mid to lower half of the sternum of the patient beneath the
97 hands of the rescuer providing CC, and CC was applied over the FDS. Because the FDS
98 technology is based on measuring acceleration, the depth calculated by the FDS
99 represents the movement of the FDS itself^{9,10} relative to the ground, not only the
100 deflection of the chest. When the patient is on a mattress, the depth reported for real-time
101 feedback is consequently the sum of both the mattress and patient chest deflection.¹¹
102 The CC data, including average rate and actual number of CC delivered, depth (mm),
103 force (kg), and type and time of audiovisual feedback prompts provided during CPR
104 event was collected in the defibrillator, and were later downloaded.

105 *Staff Education:*

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

115 *CPR event forensic engineering reconstruction:*

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

121

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

136

137 *Bed and mattress systems:*

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

147

148 *Data analysis:*

149 In this study, we defined appropriate CC depth as ≥ 38 mm. Current AHA guidelines
150 recommend CC depth of 38mm to 51mm.^{1,3,4} Based on Edelson's in-hospital report⁵, we
151 did not consider an upper limit for adequate CC depth. The primary outcome was the
152 proportion of CCs with adequate depth (≥ 38 mm) throughout an entire CPR event. This
153 proportion was compared before and after the mattress/bed correction and between the
154 two bed types (ICU bed and stretcher bed). Statistical analysis was performed by using
155 STATA 10.0 (Stata Corporation, College Station, TX). Parametric variables were
156 described by mean and standard deviation. Non-parametric variables were described by
157 median and interquartile range. Fisher's exact test was used for categorical variables.
158 McNemar test was used for paired categorical variables. T-test was used to compare
159 parametric variables. Power calculation was not done *a priori* since this study was
160 designed as a pilot descriptive study.

161

162

163 **3. Results**

164

165 From September 2006-July 2007, a total of 13 **CPR** events **occurred in** 12 patients ≥ 8
166 years old with CCs **for more than one minute because of** poor perfusion, severe
167 bradycardia or loss of spontaneous circulation in the PICU or ED. The majority (9/13)
168 were in the PICU. Among those events, FDS was used during resuscitation in 12 events
169 (11 patients), **with** 14487 CCs (202-4356 for each event). The median age of the patients
170 was 14.9 years (Interquartile range: 12.9-16.5). Table 1 summarizes patient demographic
171 data and CPR events.

172

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

180

181 The mean CC depth measured by the FDS during CPR events ranged from 37mm to
182 52mm in events on ICU beds (overall mean 47 ± 8 mm), and 42mm to 47mm in events on
183 stretchers (overall mean 45 ± 7 mm). The difference between the two bed types (ICU beds

184 with mattresses vs. ED Stretcher) was statistically different ($p < 0.0001$, two sample t-test).
185 This difference remains highly significant even after we excluded the event on the
186 Triadyne bed with deflated mattress ($47 \pm 8\text{mm}$ vs. $45 \pm 7\text{mm}$, $p < 0.0001$), and after we
187 further excluded events with an extra air-filled mattress between the patient and mattress
188 ($47 \pm 8\text{mm}$ vs. $45 \pm 7\text{mm}$, $p < 0.0001$).

189
190 The mean CC force was $34 \pm 8\text{ kg}$ for events on ICU beds and $26 \pm 8\text{ kg}$ for events on
191 stretchers. The mean calculated stiffness of the bed and mattress system was 2.7 ± 0.6
192 kg/mm for ICU beds and mattresses combined and $6.0 \pm 1.0\text{ kg/mm}$ for stretchers. Figure
193 2 displays the stiffness at the maximal CC depth.

194
195 Overall mean mattress compression calculated from the CPR reconstruction was 13 ± 4
196 mm for the ICU beds and $4 \pm 1\text{ mm}$ for stretcher beds, respectively. After compensating
197 for the mattress deflection component, the corrected mean CC depth was $35 \pm 6\text{mm}$
198 during events on ICU beds and $41 \pm 7\text{mm}$ during events on stretchers. Both compensated
199 values were significantly less than the uncompensated CC depths ($p < 0.0001$ for both,
200 paired t-tests) (Figure 3). The corrected CC depth on hospital beds was significantly less
201 than the corrected CC depth on stretchers ($p < 0.0001$).

202
203 On ICU beds, the proportion of CCs with adequate depth was 88.4 % before the
204 compensation for mattress compression, and 31.8 % after the compensation ($p < 0.0001$,
205 McNemar test). On stretchers, the proportion of CCs with adequate depth before
206 compensation was 86.3 % and 64.7% after the compensation ($p < 0.0001$). The proportion
207 of CCs with adequate depth after mattress compensation was significantly less on ICU
208 beds compared to the events on stretchers ($p < 0.001$, Fisher's exact test). Those results
209 remained significant after we excluded the event on the Triadyne bed with deflated
210 mattress, and after we excluded events with an extra air-filled mattress between the
211 patient and mattress ($p < 0.0001$ for both analysis).

212
213

214 **4. Discussion**

215
216 In this study, we report the corrected CC depth during actual in-hospital CPR in older
217 children and adolescents. When measured with an accelerometer on the sternum of the
218 cardiac arrest victim, realistic forensic engineering reconstruction of events revealed the
219 deflection of the mattress contributes approximately 28% of measured CC depth on ICU
220 beds and 10% of measured CC depth on stretchers with back boards in place. The
221 corrected CC depth with mattress compensation more accurately represents the true depth
222 of CC and quality of CPR. The proportion of CC with appropriate depth decreased
223 significantly after compensating for the mattress deflection.

224

225 Traditionally the effect of mattress deflection has been ignored during real in-hospital
226 CPR. Recent clinical studies analyzed quality of CPR in actual resuscitation, but did not
227 consider the mattress deflection.³⁻⁵ Even without considering mattress deflection during
228 CPR, the reported CC depth described herein was often too shallow. In the first two
229 quality of CPR studies with use of FDS as data collection method, shallow CCs were

230 observed in 37.4% of compressions during in-hospital adult CPR and in 59% of
231 compressions during out-of-hospital adult CPR. **The** mean CC depth was 42 mm during
232 in-hospital and 35mm during out-of-hospital CPR.^{3,4} Those differences can be
233 attributable largely to presumed differences in compliance in mattress support systems
234 (hospital bed in the former, and the stretcher/floor surface in the latter). If the data were
235 compensated for mattress deflection, the reported CC depth **would** be even shallower
236 especially in in-hospital CPR. In our study, the measured CC depth was larger than
237 reported in those two studies. Intensive initial and refresher training, and real time
238 feedback with FDS technology all perhaps contributed to this difference.

239

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

245

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

257

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

267

268 Our study demonstrated the substantial effect of the support system under the patient on
269 **the** actual depth of CCs and on the degree of overestimation of the quality of CPR based
270 on the FDS placed on the sternum during real CC. The softer (less stiff) ICU bed and
271 standard mattress combination was associated with shallower true CCs and larger
272 overestimation by quality of CPR feedback systems, compared to stretchers with a thin
273 mattress. Furthermore, the difference between actual CC depths and measured
274 (unadjusted) CC depth among the various types of hospital beds (deflated Triadyne bed,
275 ICU bed with an air mattress, and ICU bed with a standard mattress) were much larger

276 compared to the CPR events on ED stretchers. Those findings were consistent with
277 Perkins's study.²³ He reported significantly shallower mattress compensated
278 compressions in adult manikins on foam (35.2±5.6 mm), inflated (37.2±6.3mm), and
279 deflated (39.1±5.6 mm) mattresses compared to the hard-surface floor (44.2±5.2mm) by
280 using a manikin with an internal depth measurement device. He speculated this
281 significant difference may be due to: 1) use of the constant displacement model by chest
282 compressors (i.e., compressors unintentionally attempt to provide the same chest
283 compression depth measured from surface of the chest despite the mattress deflection), 2)
284 presence of manikin on a hospital bed *per se* impairs CC **delivery**. Although both of **these**
285 explanations probably contributed to our observation, our experimental design does not
286 allow further clarification.

287
288 Our study results need to be interpreted in light of several important limitations.
289 During CPR **typically** multiple providers performed CCs. We did not record and control
290 for provider characteristics, **previous training status** and demographic data for those who
291 provided CCs. It is possible that the automated directive and corrective feedback system
292 guided the CC providers to compress too shallow, **because** the automated audiovisual
293 feedback system is **derived from** the uncorrected **CC** depth measured by FDS. However, a
294 recent study showed the CC depth without feedback is actually shallower than
295 compression depth with such feedback.⁶ The mattress deflection was not directly
296 measured with a reference accelerometer simultaneously on the bed during the real CPR
297 event, rather it was estimated based on the measured force applied during CPR events and
298 on the mattress stiffness model using the compression depth and the applied force during
299 forensic engineering reconstruction. However, forensic reconstruction of the events was
300 conducted using the actual bed that was used during real CPR, with the size, shape and
301 placement of the backboard precisely reproduced to minimize artifacts.
302 **Although the error in FDS depth measurement on adult cadaver and manikin is within 3**
303 **mm, there is no FDS depth measurement accuracy data in children.**

305 **5. Conclusions**

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

315 **6. Conflict of Interest**

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323

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