Clinical paper

Excessive chest compression rate is associated with insufficient compression depth in prehospital cardiac arrest

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\textbf{Abstract}

\textbf{Background and goal of study:} The relationship between chest compression rate and compression depth is unknown. In order to characterise this relationship, we performed an observational study in prehospital cardiac arrest patients. We hypothesised that faster compressions are associated with decreased depth.

\textbf{Materials and methods:} In patients undergoing prehospital cardiopulmonary resuscitation by health care professionals, chest compression rate and depth were recorded using an accelerometer (E-series monitor-defibrillator, Zoll, USA). Compression depth was compared for rates 80–120/min and >120/min. A difference in compression depth <0.5 cm was considered clinically significant. Mixed models with repeated measurements of chest compression depth and rate (level 1) nested within patients (level 2) were used with compression rate as a continuous and as a categorical predictor of depth. Results are reported as means and standard error (SE).

\textbf{Results and discussion:} One hundred and thirty-three consecutive patients were analysed (213,409 compressions). Of all compressions 2% were <80/min, 62% between 80 and 120/min and 36% >120/min. Differences were 0.4 cm deep, 45% between 4 and 5 cm, 19% >5 cm. In 77 out of 133 (58%) patients a statistically significant lower depth was observed for rates >120/min compared to rates 80–120/min in 40 out of 133 (30%) this difference was also clinically significant. The mixed models predicted that the deepest compression (4.5 cm) occurred at a rate of 86/min, with progressively lower compression depths at higher rates. Rates >145/min would result in a depth <4 cm. Predicted compression depth for rates 80–120/min was on average 4.5 cm (SE 0.06) compared to 4.1 cm (SE 0.06) for compressions >120/min (mean difference 0.4 cm, P < 0.001). Age and sex of the patient had no additional effect on depth.

\textbf{Conclusions:} This study showed an association between higher compression rates and lower compression depths. Avoiding excessive compression rates may lead to more compressions of sufficient depth.

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1. Introduction

Following the International Consensus on Science and Treatment Recommendations on Resuscitation, the European Resuscitation Council (ERC) 2010 Guidelines for Cardiopulmonary Resuscitation (CPR) recommend for rescuers to compress the sternum of an adult victim of cardiac arrest “at least 5 cm (but not more than 6 cm)” at a rate of “at least 100/min (but not more than 120/min)”.\textsuperscript{1,2} The previous ERC Guidelines (2005) recommended to compress the sternum “4 to 5 cm” at a rate of “about 100/min”.\textsuperscript{3} The main reason for this change in guidelines is studies showing that deeper compression depth is associated with higher success of defibrillation and a higher chance of admission to hospital.\textsuperscript{4,5} Therefore, sufficient compression depth is key to survival. Professional rescuers, however, often do not deliver high quality CPR regarding compression rate and depth.\textsuperscript{6–8} The reasons for these are not fully known. Recently, Field et al. found that compression depth decreased from 4.0 cm at 80/min to 3.5 cm at 160/min when health care professionals performed continuous compressions on a manikin.\textsuperscript{9} Their results suggest an inverse relationship between compression rate and depth. The latest Consensus on Science and
Treatment Recommendations on Cardiopulmonary Resuscitation (2010) recognised the knowledge gaps in the relationship between compression rate and depth.\textsuperscript{1} In order to characterise the relationship between compression rate and depth, we performed an observational study in prehospital cardiac arrest patients.

2. Methods

2.1. Aim of the study

The aim of the study was to quantify the relationship between compression rate and compression depth during prehospital cardiac arrest by professional rescuers. Our hypothesis was that higher compression rate is associated with lower compression depth.

2.2. Procedure

This observational study was conducted in the Ghent area with a population of approximately 150,000 inhabitants. From March 2009 until October 2010 all prehospital resuscitation events attended by the physician-staffed second tier ambulance of Ghent University Hospital were registered with a Zoll E-series defibrillator and CPR-D Padz\textsuperscript{®} (Zoll, Chelmsford, USA) The ambulance was staffed by an emergency medical technician, a nurse specialised in emergency medicine and a resident or consultant in emergency medicine or anaesthesiology. ERC Guidelines 2005 were followed. All patients were resuscitated on a solid surface. In most cases, a first tier ambulance staffed with two emergency medical technicians would also be at the scene, ensuring chest compression during advanced life support. The Ethics Committee of Ghent University Hospital approved the study and allowed deferred consent.

2.3. Materials

Immediately after arrival of the second tier ambulance, CPR-D Padz\textsuperscript{®} were placed on the victim's chest according to the manufacturer's instructions. The CPR-D Padz\textsuperscript{®} incorporate an accelerometer measuring displacement of the chest during compressions. The defibrillator provided real-time audible and visual feedback of compression quality (rate and depth). A sliding window of five compressions was analysed. If the recorded depth failed to achieve 4 cm in three of the five compressions, the unit periodically generated a voice prompt saying, “push harder” When the four cm threshold was achieved in two of three compressions, the “good compression” voice prompt was played. According to the manufacturer, the accuracy of the compression depth measurement was ±0.6 cm 95\% of the time.\textsuperscript{10} Compression rates below 80/min resulted in the automatic activation of a metronome sounding at a rate of 100/min. In addition to the audible feedback, visual feedback was provided consisting of a display showing a vertical bar for every compression indicating depth, plus a horizontal bar indicating overall good compression depth and rate when full. As an inherent feature of the Zoll software, potentially excessive compression depth or rate was not corrected.

2.4. Data collection

For every compression, the defibrillator automatically stored depth, rate and a time stamp on a memory card that was uploaded after the event with RescueNet\textsuperscript{TM} Code Review, Enterprise Edition version 5.12 (Zoll, Chelmsford, USA). The resulting files were exported in a text format and imported into Excel for Windows. For each compression the rate was then calculated using the time interval to its preceding compression. Therefore the first compression of a series of compressions was not taken into account. Data on sex of the patient, age, presenting rhythm and return of spontaneous circulation were extracted from the ambulance run sheets.

2.5. Inclusion and exclusion criteria

Inclusion criteria for analysis were: presence of informed consent and age of 18 years or more. Exclusion criteria for analysis were the absence of a data file (accelerometer not applied or a technical problem), an incomplete data file or resuscitation performed in a driving ambulance generating random compression data.

2.6. Statistical analysis

To examine the relationship between chest compression depth and rate, a mixed model was used with repeated measurements of chest compression depth and rate (level 1) nested within patients (level 2). Multilevel models have several advantages: they use all available data, can properly account for correlation between repeated measurements on the same subject, can handle missing data adequately, and have great flexibility to model time effects.\textsuperscript{11–13} Different specifications of the variance-covariance structure were considered and model selection was based on the procedures described in Verbeke and Molenberghs,\textsuperscript{11} information criteria (Akaike Information Criterion, Bayes Information Criterion) and interpretability of the results. First, a mixed model was estimated with chest compression depth as criterion, fixed linear and quadratic effects for chest compression rate as time-varying predictors, age and sex as time-invariant covariates, and random intercepts and random linear (subject-specific) slopes as random effects. For inference on the fixed effects, the Kenward–Roger denominator degrees of freedom method was used. This model (without the terms that were not significant) was used to make compression depth estimates (and 95\% confidence intervals) at particular values of compression rate. In addition, a similar mixed model was estimated but with compression rates divided into a categorical variable comprised of three categories: <80/min, 80–120/min, and >120/min. P-Values are reported as two-tailed. A P < 0.05 was considered significant. Statistical analysis was performed using Statistical Analysis Software (SAS) (version 9.2, Cary, NC, USA).

3. Results

3.1. Demographics

Demographic data are shown in Table 1.

3.2. Compression data

Out of the 161 eligible patients, 133 patients could be analysed. Each subject had on average 1605 (SD 1068, min 86, max 5108)

| Table 1: Demographics. SD: standard deviation; VF: ventricular fibrillation; VT: ventricular tachycardia; PEA: pulseless electrical activity; ROSC: return of spontaneous circulation. Values as mean (SD) or count (percentage). |
|---------------------------------|----------------|----------------|----------------|
| Age (years)                     | Included patients n = 133 (83\%) | Excluded patients n = 28 (17\%) | P-values |
| Female                          | 67 (16) | 61 (18) | 0.13 |
| Initial rhythm                  | 41 (31\%) | 6 (21\%) | 0.32 |
| Asystole                        | 93 (70\%) | 17 (61\%) | 0.32 |
| VF/VT                           | 18 (14\%) | 4 (14\%) | 0.27 |
| PEA                             | 22 (16\%) | 7 (25\%) | 0.27 |
| ROSC                            | 56 (42\%) | 15 (53\%) | 0.27 |
repeated measurements of chest compression rate and depth (a total of 213,409 compressions).

Of all compressions, 36% were <4 cm deep, 45% between 4 and 5 cm, 19% >5 cm, 2% were <80/min, 62% between 80 and 120/min and 36% >120/min. Thirty percent of all compressions were performed with a correct depth and rate according to the ERC 2005 Guidelines. Fig. 1 shows the distribution of compression depth per rate category. In 95 out of 133 (71%) patients the mean compression depth in the rate category >120/min was lower than in the category with compression rate between 80 and 120/min; in 77 out of 133 (58%) this difference in compression depth was statistically significant. In 40 of 133 (30%) the difference was considered clinically significant because the mean depth decreased with 0.5 cm or more. Table 2 shows the results of the mixed model that examines the relation between chest compression rate and depth with age and sex of the patient as covariates. The linear regression weight for compression rate (0.03) indicates that chest compression depth increases with increasing chest compression rate but the negative quadratic regression weight for chest compression rate (−0.0002) indicates that this linear increase levels off and turns into a decrease in chest compression depth at higher chest compression rates. This is illustrated in Fig. 2, showing that chest compression depth slowly increases for chest compression rates between 20 and 86/min; from then on, a higher chest compression rate results in a smaller chest compression depth (first slowly but later on more quickly). At 86/min, the deepest chest compression is predicted being 4.5 cm (95% CI 4.3–4.7). At 100/min and 120/min, the estimated chest compression depths are 4.5 cm (95% CI 4.3–4.6) and 4.3 cm (95% CI 4.1–4.4), respectively. Rates of more than 145/min would result in depths below 4 cm (the upper 95% CI limit of the estimated depth at a rate of 145/min is 4 cm implying that under resampling the estimated compression depth at 145/min would be below 4 cm in 95% of the cases). At lower compression rates, compression depth remains fairly stable and only at a predicted rate of 34/min, compression depth reaches the lower limit of 4.0 cm. Very low compression rates were uncommon, therefore the clinical significance of this finding is limited.

In general, we conclude that compression depth remains above 4 cm over a wide range of rates, but excessively fast compressions lead to insufficient depth. Furthermore, Table 2 shows that there are no significant effects of age and sex of the patient.

Next, a mixed model was used with chest compression rate as a categorical predictor. Categorisation according to the 2005 Resuscitation Guidelines resulted in very unbalanced categories: 2% (<80/min), 62% (80–120/min) and 36% (>120/min).

The estimated chest compression depth for the three categories is depicted in Table 3. This analysis confirms that chest compression depth is significantly different between the three categories, \( F(2, 210,000) = 4424.94, P < 0.0001 \). In line with Fig. 2, chest compression depth was maximal at a chest compression rate in the category 80–120/min and less deep in the adjacent categories. This model also shows that age and sex were not significantly different, respectively, \( F(1, 130) = 1.56, P = 0.21, F(1, 130) = 0.05, \) and \( P = 0.82 \).

### 4. Discussion

We showed that, during prehospital resuscitation by professional rescuers, compression rates between 80 and 120/min were associated with deeper compression depths as compared to rates >120/min. A difference of 0.5 cm depth was considered clinically significant because Edelson and colleagues showed that every 0.5 cm increase in compression depth doubled the odds of successful defibrillation. Moreover, using a multilevel model we showed that the predicted deepest compression depth (4.5 cm) occurred at a rate of 86/min. From thereon, compression depth declined gradually and only at a rate of about 145/min compression depth would become unacceptably low according to the ERC Guidelines 2005. Our findings support the results from a manikin study by Field et al. showing that faster compressions lead to reduced compression depth.9 In our study, high compression rates were common and may be explained by stress or by the inability of rescuers to assess and control the compression rate. Very low compression rates were uncommon and may be associated with specific activities potentially interrupting chest compressions such as aspiration, intubation and defibrillation.

We have measured compression depth and rate using accelerometer technology with feedback. Feedback during CPR has

### Table 2

<table>
<thead>
<tr>
<th>Fixed effects</th>
<th>Regression weight (SE)</th>
<th>F test (df, df)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear effect</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rate (per min)</td>
<td>0.03287 (0.002084)</td>
<td>( F(1, 163) = 248.77 )</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Quadratic effect</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rate (per min)</td>
<td>−0.00019 (0.000003)</td>
<td>( F(1, 210,000) = 3840.31 )</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sex</td>
<td>0.03140 (0.1417)</td>
<td>( F(1, 130) = 0.05 )</td>
<td>0.83</td>
</tr>
<tr>
<td>Age</td>
<td>−0.00772 (0.004136)</td>
<td>( F(1, 130) = 3.49 )</td>
<td>0.06</td>
</tr>
</tbody>
</table>

### Table 3

Prediction of chest compression depth (cm) based on chest compression rate divided into three categories with age and sex as covariates: estimated means. SE: standard error. All three means differ pairwise at \( P < 0.0001 \) in an adjusted Tukey-Kramer comparison.

<table>
<thead>
<tr>
<th>Least square mean estimate (SE)</th>
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<tbody>
<tr>
<td>&lt;80/min</td>
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<tr>
<td>80–120/min</td>
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<tr>
<td>&gt;120/min</td>
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</tbody>
</table>
shown to improve the quality of CPR but an effect on survival has not been demonstrated.\textsuperscript{14,15} The Zoll defibrillator did not correct rescuers who compressed too fast. On the other hand, the defibrillator activated a metronome at 100/min when compression rate was <80/min. Manikin studies have shown that a metronome not only guides compression rate but can also increase or decrease compression depth.\textsuperscript{9,16–19} Chung and colleagues reported that an increase in rate also increased compression depth in a manikin study.\textsuperscript{17} This is in contrast with the findings by Field et al. who reported the opposite.\textsuperscript{9} Potential explanations for the decrease in compression depth in the Field study may be the longer compression periods as compared to the Chung study (2 min versus 1 min), the shorter recovery periods between each compression period (3 min versus 20 min), and the higher compression rates (up to 160/min versus 140/min), all potentially leading to more fatigue and probably reflecting reality better.

To prevent loss of compression depth, rescuers should be advised not to compress at rates exceeding 145/min. The mechanism whereby excessively fast compressions lead to insufficient depth is unknown, but may be linked to patient-related factors such as chest mechanics, and rescuer-related factors such as physical inability to deliver deep compressions at high rates and fatigue.

A first limitation of the study is that the results were obtained with specific feedback provided by the Zoll E series defibrillator. Because the specific instructions by the defibrillator were not recorded, it is unknown to what extent rescuers followed the instructions and how they were influenced by them. Furthermore, it cannot be excluded that other feedback systems may influence the relationship between compression depth and rate differently. Second, apart from age and sex, other patient factors such as chest compliance are likely to influence the relationship between compression rate and depth, but because the Zoll technology does not incorporate a pressure sensor, we were unable to measure them.\textsuperscript{20} Third, rescuer-related characteristics (weight, height, fatigue) were not studied because during a resuscitation attempt by an advanced life support team several rescuers alternate at delivering compressions and it is currently not possible to determine the individual contribution of each rescuer. Fourth, although incomplete release is an important determinant of the quality of resuscitation, the defibrillator was not able to measure it. Fifth, our study was performed using feedback according to ERC Guidelines 2005. As the ERC Guidelines 2010 recommend a depth of “at least 5 cm”, this may change to the relationship between compression rate and depth.

5. Conclusions

Using a defibrillator with an accelerometer measuring compression rate and depth, in about one third of cardiac arrest patients compression rates >120/min were associated with a clinically significant lower compression depth as compared to compressions of <120/min. In a predictive model, deepest compressions were provided at a rate of 86/min, and a depth of <4 cm occurred at a compression rate of >145/min. Avoiding excessive compression rates may lead to more compressions of sufficient depth.

Conflict of interest statement

The authors report no conflict of interest related to the study.

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